Ontario

Ministry of the
Environment

Hon. George A. Kerr, Q.C., *Minister*
Everett Biggs, *Deputy Minister*

Water Resources
Paper 6

Ice Effects and Related Corrections to Winter Streamflows in Small Streams

WATER RESOURCES
PAPER 6

ICE EFFECTS AND RELATED CORRECTIONS TO WINTER STREAMFLOWS IN SMALL STREAMS

By

R. B. Jaffray

MINISTRY OF THE ENVIRONMENT

WATER RESOURCES BRANCH

TORONTO ONTARIO

1975

PREFACE

In conducting hydrologic studies, the availability of accurate streamflow data often governs the reliability of the results of such studies and their pertinent conclusions and recommendations. In conducting these studies under the adverse winter conditions found in Ontario, specialized procedures have been adopted by the Ministry of the Environment staff, in an attempt to provide accurate records of streamflow in several representative basins for the International Hydrological Decade program.

This report outlines the various techniques that can be used to collect and analyse records of streamflow obtained during periods of ice formation. As an aid in the field measurement of streamflow and in the interpretation of ice-affected records, several precautions can be taken in attempting to lessen the effects of the formation of ice in streams.

The guidelines as presented in this report can be used by technicians and technologists working in the collection and analysis of streamflow data.

G. H. Mills

Toronto, March 1, 1975

TABLE OF CONTENTS

	Page
PREFACE	
ACKNOWLEDGEMENT	
INTRODUCTION	1
ICE FORMATION (GENERAL)	2
Surface Ice	2
Surface Ice Layering	3
Frazil Ice	4
Anchor Ice	4
EFFECTS OF ICE ON THE STAGE-DISCHARGE RELATIONSHIP	6
Surface Ice Effects	6
Siphon Effects	7
Ice Jamming	9
Ice Channels	9
Surface Ice Layering Effects	10
Frazil Ice Effects	10
Anchor Ice Effects	10
METHODS AND TECHNIQUES OF ICE CORRECTION	10
Discharge Correction Method	11
Gauge Height Correction Method	12
Interpolated Correction Method	13
CASE STUDIES - Ice Formation Effects on the Stream-stage Hydrograph and Consequent Corrections	14
Surface Ice Corrections	15
Siphon Corrections	18
Ice Jamming Corrections	21
Ice Channelling Corrections	22
Surface Ice Layering Corrections	23
Frazil Ice Corrections	23
Anchor Ice Corrections	24
ICE PREVENTION	25
Selection of Site and Control Structure Characteristics	25
Ice Prevention in the Stream Channel	26
Ice Prevention in the Gauge-House Stilling Well and Intake Pipe	27

	Page
CONCLUSIONS	29
SELECTED REFERENCES	30
APPENDICES	
Appendix A - Location Maps	
Appendix B - Stream-stage Hydrographs and Ice Corrections	
Appendix C - Ice Sheets	

ACKNOWLEDGEMENT

Staff assistance in providing the essential information for the preparation of this report is gratefully acknowledged.

The author, Mr. B. Jaffray, at the time of the writing of the report, was a technologist with the former River Basin Research Section of the Water Quantity Management Branch. Mr. Jaffray is now with the Ministry's Southwestern Region (London, Ontario) in the Technical Support Group.

INTRODUCTION

The former River Basin Research Section of the Ontario Ministry of the Environment contributed to the International Hydrological Decade program by studying the hydrologic conditions of five representative basins in Southern Ontario, (Map 1, Appendix A).

A portion of the work undertaken for this program dealt with instrumentation for the collection and analysis of streamflow data in each basin. During the open-water period, records of flow, as determined for various stations within each basin, were derived using primarily two sources of information - a continuous hydrograph of the stream water-level stage controlled by a critical stream cross-section or an artificially constructed 'control', and a corresponding 'rating curve' or stage-discharge relationship derived from instanteous discharge measurements at each station. The stage-discharge relationship was then applied to allow the calculation of continuous discharge records for corresponding water-level readings to derive flow records for the open-water periods.

In an attempt to provide accurate and continuous records of flow during the winter period, the data collection activity of the former River Basin Research Section was developed into a systematic operation of field observations accompanied by individual office interpretations.

This report deals with the collection and analysis of streamflow data for winter periods when ice phenomena cause erratic changes to the recorded water-level stages. It also outlines the procedures that can be followed in order to correct these effects and obtain improved discharges.

The water courses or streams studied in the IHD basins were relatively small in size, the average discharges during the winter periods being in the range of two to four cubic feet per second (cfs). The maximum velocity was usually less than 1.3 feet per second, occurring in stream sections not greater than 12 feet in width.

As the representative basins were located in five different physiographic regions, each having somewhat different physical and climatological environments, varying winter conditions existed in the basins and at the individual streamflow gauging stations within each basin. The interpretation of winter streamflows, therefore, was carried out on an individual site basis, using the prior behavioural and functional knowledge of each of the specific stations in question.

ICE FORMATION (GENERAL)

During the autumn and early winter period, the water temperatures in streams begin to decrease due to heat losses at the air-water interface. The heat exchange at this surface is influenced by air temperature, net radiation, convection and evaporation losses.

The major factor influencing the rate of cooling of a stream is the difference between the mean air temperature and the mean water temperature. As stated by Newton's law of Cooling: 'The rate of cooling of a body is proportional to the difference in temperature between the body and its surroundings'. Heat losses can be due to other factors, such as net radiation, which will vary with the inclination of the sun, the percentage and type of cloud cover and the condition of the water surface. Convection losses will vary with the speed and direction of the wind, the degree of air turbulence and the air temperature. Evaporation losses will depend on the vapour pressure gradient existing between the surface of the water and the air mass, as well as the wind velocity and condition of the surface.

The condition of the surface affects both radiation and evaporation losses by influencing the albedo, i.e. the amount of radiation that is reflected. With high albedo, heat losses from a water body to the atmosphere decrease. Heat loss from the stream is also influenced by the heat carried into and out of a stream section by the flowing water itself, by the heat received from ground-water discharging directly into the stream and by the heat exchange at the water-streambed interface.

As the heat loss from the water surface continues, the cooled water on the surface is continuously replaced by warmer water from below.

In small streams, as a result of the small amount of flow present and the shallow depths encountered, the water body is constantly being inter-mixed and the entire water section soon reaches a temperature of 32°F. As the cooling continues, the water near the surface becomes supercooled and ice crystallization begins. In general, three types of ice - surface, frazil and anchor ice - can be observed to form under varying physical and atmospheric conditions.

Surface Ice

Surface, or sheet ice, is the most common type of ice formation, developing during below-freezing air temperatures and under certain flow velocities.

As previously outlined, the ice-forming process is initiated as the water body is gradually cooled. As it reaches 32°F, the upper layer of the water surface is supercooled to a temperature slightly below that of freezing. Due to this supercooling, ice crystals begin to form on the surface of the water near the stream bank and on solid matter suspended or floating in the water. The rate of growth and the amount of ice that forms are determined by both the length and severity of the cold period and by the amount and temperature of extraneous inflow into the stream that may bring about additional heat exchange. The ice formation is also affected by the velocity of the water, the characteristics of the streambed and by fluctuations in stage, caused by both natural and artificial constrictions, all of which tend to agitate the water surface. Surface ice will generally not form with water velocities greater than 1.5 feet per second.

If conditions are such that they continue to favour ice growth, ice crystals continue to form at the water-ice interface, increasing the ice cover in extent and thickness until the entire stream surface is spanned.

Once the initial ice layer has formed on the water surface, the changes in the growth of the layer will be dependent upon the heat exchange between the water and the air through the ice layer. The temperature gradient through the ice will decrease as the ice thickness increases and this results in a gradually slower rate of ice growth at the water-ice interface.

The ice layer may also be thickened by the accumulation and freezing of precipitation on the upper side of the ice cover. If there is an insulating layer of snow on the ice, the temperature gradient will be further reduced and the rate of growth of the ice thickness will decrease accordingly.

Specifically in relation to a streamflow gauging station, surface ice formations first develop under the slower velocity conditions in the areas immediately upstream and downstream of the control . At the same time, ice particles form at the ends of the control where the water velocities are also slower. The faster water velocities in the center of the control retard the formation of ice in that area, (Photograph 1). With the continuing of depressed temperatures or the further decrease in temperatures and consequent increased supercooling of the water surface, ice formation progresses towards and around the control.

Surface Ice Layering

During the winter period, as air temperatures increase to levels above freezing, the snow cover in a drainage basin begins to melt, producing runoff. Often, thaw conditions are

accompanied by rainfall which further contributes directly to the rate of snowmelt and runoff. If there is a thick initial surface ice layer on a stream, warmer temperatures may initiate surface runoff from land before the ice layer on the stream melts or is completely melted. These conditions can result in water flowing over the top of the surface ice. As the temperature of this water will be only slightly above freezing and as the water layer acts as insulation, the ice layer beneath the flowing water is not reduced significantly. When the air temperature returns to a freezing level or below, surface ice formation will begin, thereby producing a second layer of ice. An ice layering condition is thus produced that may have either flowing water or slush ice between the two ice layers. The freeze-thaw cycle can repeat itself to create a number of ice layers on a stream.

In the field, the condition of ice layering cannot be readily recognized by visual inspection of either the frozen stream or the graphical chart record from a gauging station, but only by cutting a hole through the top surface ice to determine if there are other ice layers beneath.

Frazil Ice

Frazil ice forms in streams where the velocity of flow or wind disturbance on the surface is sufficient to prevent the formation of surface ice. Frazil ice formation begins with the appearance of thin circular ice disks which grow outwards from their edges to form flat 'dendrites', which continue to grow outwards to produce needle-like fragments. These fragments form rapidly and group together into large, porous, spongy masses or packs. When a stream is not extremely turbulent, the frazil ice packs tend to remain submerged and adhere to each other, building up on underwater objects that have temperatures of 32°F or less. The formation of frazil ice never occurs in quiet water under an ice cover but only under turbulent water conditions; however, it may be carried by water currents to jam and compact under a surface ice cover further downstream.

Anchor Ice

Anchor ice, which resembles frazil ice in structure, forms under the water surface in turbulent water areas of a stream channel and adheres to a streambed and objects in the streambed. Anchor ice usually forms between sunset and sunrise when the long-wave radiation emitted by objects to which the anchor ice can adhere is at a maximum. When heat is lost from submerged objects, the surrounding supercooled water crystallizes on them. In the same manner as for the formation of frazil ice, anchor ice only builds up

below an open-water surface. Under a surface ice cover the insulating effect of the ice reduces the amount of escape to the atmosphere of long-wave radiation emitted by the streambed, thereby preventing anchor ice formation.

During the daylight hours, a sufficient amount of short-wave radiation may be absorbed by the water to raise the temperature of the water, causing the release of the anchor ice. Anchor ice may also be released from the streambed when it has sufficient buoyancy to overcome the adhesive forces that hold it to the streambed. It then floats to the surface where it may be washed away and compacted against or under surface ice further downstream.

Photograph 1.
Initial surface ice formation at gauging station W-3, looking upstream

Photograph 2.
Anchor ice detached from streambed at gauging station B-3

EFFECTS OF ICE ON THE STAGE-DISCHARGE RELATIONSHIP

Natural streamflow hydraulics are usually altered by the formation of any of the previously described ice forms; however, the continuous recording of the water-level (gauge height) at streamflow gauging stations, and consequently the calculation of the corresponding discharges, are not affected by ice formations unless the ice produces physical changes, either directly or indirectly, to the controlling cross-section. The controlling section for a streamflow gauging station is that section of the stream (which can be a weir, series of rapids or a gravel bar, etc.) that produces a fixed water-level elevation for a specific discharge.

If the controlling stream section is affected by ice formation, a false rise in gauge height is produced and the stage-discharge relationship developed for the open-water period can no longer be applied. Standard discharge calculation procedures, therefore, cannot be followed without first quantifying and correcting for the effects of the ice formation.

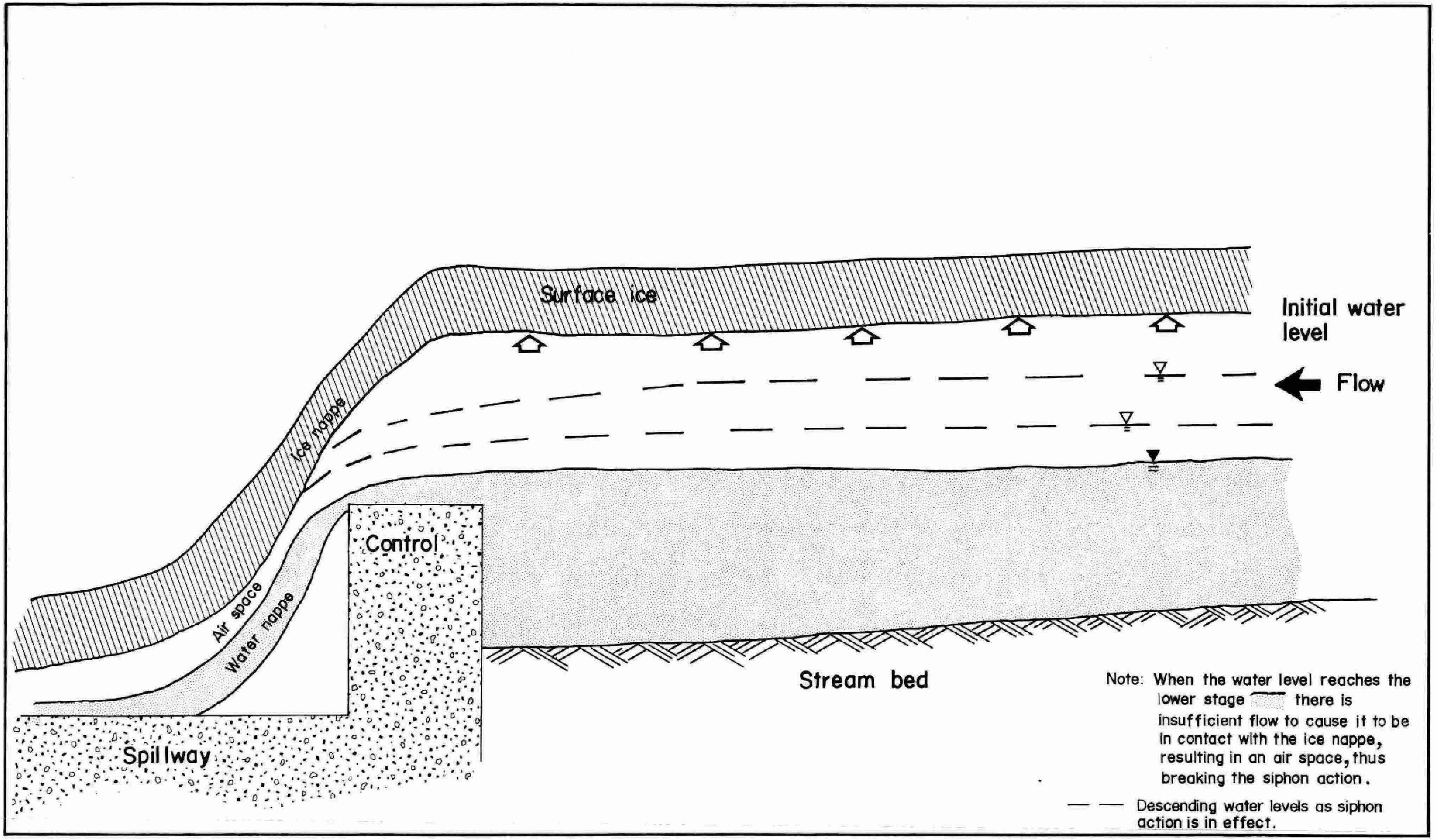
Surface Ice Effects

Surface ice will affect the controlling section by confining the cross-sectional area of discharge, thereby altering the stage. Surface ice may consist of a partial to full ice cover, complete ice cover bridging the control, or alternating layers of ice and water at the controlling section.

The stage can also be affected by ice jams forming in the channel downstream of the control, thereby causing backwater allowing a rise in the water level sufficient to cause either partial or total submergence of the control.

As surface ice begins to form and advances inward from the edges of a control, it also grows downward into the water section and may become attached to the material that comprises the controlling section. This will produce a restricting effect on the flow as the cross-sectional area of the normal open-water controlling section is subsequently reduced. The flow is displaced upward, producing backwater in the weir pond and consequently a false gauge height recording.

As the weir pond becomes frozen over, the backwater that is produced at the control results in a pressure against the under-surface of the ice. As the stilling well in the streambank, used for recording the water-level fluctuations, is directly connected to the weir pond, this pressure under the ice is transferred to the well and evidences itself as a false gauge height in the continuous recording of the streamflow hydrograph.



Drawing 1. Theoretical illustration of siphon action at station B-1.

Depending on the velocity of flow over the control and the associated atmospheric conditions, the ice may eventually produce a complete cover over the control. When this occurs, a further restriction may be placed on the flow, producing a larger amount of backwater. This restriction may not be constant over a long period of time but may vary, mainly with the air and stream temperatures, causing the bridging layer of ice to further build up or melt. Ice bridging of the control, however, does not always have a restricting effect, as there may be an air space between the water surface and the ice.

Siphon Effect

With the formation of surface ice at certain gauging stations, a phenomenon described as 'siphon' action is sometimes produced. This situation generally occurs at stations which have artificial controls and where there is distinguishable freefall over the control.

As indicated earlier, pressure is developed under the ice in the weir pond, causing a false rise in gauge height. With flow continuously entering the weir pond, the pressure under the surface ice increases and in turn produces an increase in the flow velocity through the enclosed conduit of the constricted cross-sectional area of the control. As this is a closed system, the increase in velocity can result in a larger quantity of flow going through the constricted area of the control than is entering the weir pond. With this increase in discharge, water is drawn out of the weir pond, reducing the confining pressure and causing the recorded stage to drop. The pressure and the recorded stage can continue to decrease, even to a point below that which would be the corresponding normal water-level recorded under open-water conditions. The siphon effect continues as long as a closed hydraulic system is maintained, i.e. until air enters the system at some point. When the water is flowing out of the weir pond, the volume through the enclosed conduit at the constricted area of the control is usually large enough to keep the water nappe in contact with the covering ice nappe forming the closed system. However, once the water level drops to a critical stage, there is insufficient pressure in the weir pond to retain the closed system and an air space is created between the water nappe and the ice nappe, thereby breaking the siphon action (Drawing 1). As the flow returns to pre-siphon conditions, discharge at the control is again restricted and increases less than the incoming streamflow to the weir pond and another siphon action results.

An example of this phenomenon can be taken from streamflow gauging station B-1 in the Bowmanville, Soper and Wilmot Creeks IHD representative basin, for the period of January 2 - 11, 1968 (Map 2, Appendix A). The stream-stage hydrograph (Figure 5, Appendix B) shows a false increase in gauge height caused by the restricting surface ice formed at the control during an extremely cold temperature period. During January 7 and 8, ice covered the weir pond, completely bridged the control and also formed on the surface of the water nappe discharging over the control. This ice nappe then became attached to the ice that had formed over the control spillway; in effect an enclosed conduit was produced over the control spillway. This conduit extended from the weir pond to the downstream spillway area (Photograph 3). The stream-stage hydrograph

for Station B-1, (Figure 5, Appendix B), shows that the formation and breaking of the siphon action can be a fast-occurring phenomenon. A complete siphon cycle can occur within two minutes.

The receding trace of the hydrograph from January 9-11 indicates that the amount of backwater in the weir pond was gradually being reduced. This reduction in backwater can likely be attributed in part to a decrease in incoming streamflow. However, as a relatively constant discharge of ground water contributes to flow in this water-course, the reduction in backwater can also be attributed to a decrease in the thickness and the extent of the ice formation at the control. As the increase in the air temperature during this period was insufficient to cause a significant enough rise in the water temperature to produce any melting of the ice cover, it is assumed that the decrease in the ice at the control was caused by the effect of electrical heat in the control, combined to some extent with the erosive action of the water on the under-surface of the ice.

When the amount of ice at the control decreased, the thickness of the ice nappe also decreased, thereby gradually reducing the magnitude of the fluctuation of the siphon effect. This is evident on the hydrograph during the period from 1445-2000 hours on January 9. Water pressures as a result of decreased backwater appear to have gradually declined until there was insufficient pressure in the weir pond to produce the velocity required to restart the siphon action.

The ice layer at the control and the consequent backwater appear to have gradually decreased until January 11, when no further effects on flow-conditions were evident.

The following conditions appear essential for the development of a siphon action:

1. Surface ice must completely bridge over the control, so that the normal cross-sectional area of flow is constricted and an ice nappe must form over the water nappe. If ice extends only up to the control, no ice nappe is present to create a closed siphon.

2. The normal air space between the under-surface of the ice and the water surface must be displaced by the backwater produced at the control. The system must form a closed conduit in order to produce siphon action. If the air space under the ice is connected to the atmosphere, the system is not a closed conduit and siphon action cannot occur.

3. For a siphon action to start, a critical flow velocity over the control must be reached. This critical velocity will vary with the type of control and local ice conditions.

Siphon action is also explained by alternating pressures in an air space between the under-surface of the ice and the water (5). The writer believes, however, that siphon action is mainly caused by fluctuating water pressures under the ice and by increasing flow velocities at the controlling section; an air space only becoming evident when siphon action is disappearing.

Ice Jamming

At the beginning and the end of the ice-formation period, surface ice may not be prominent at a controlling section, but may form in other areas of the stream channel. The formation of surface ice in the stream channel will not usually directly affect the recorded gauge height at the control. In some instances, however, its formation in the downstream area could have a significant influence on the water-level fluctuations at the controlling section. For example, the formation of ice in the downstream channel may act as a barrier upon which floating ice may accumulate or jam. If a sufficient amount of ice builds up in this manner, the cross-sectional area of the channel may be reduced at that point and consequently the effective carrying capacity of the stream is reduced, resulting in backwater. If ice jamming is of significant magnitude to produce backwater at the control, causing its submergence, a false gauge height can be recorded.

Ice Channels

Formation of ice in the weir pond may alter the open-water flow pattern, if the underside of the ice forms unevenly. In forming unevenly, the underside of the ice cover may eventually create separated flow channels. These flow channels may or may not be connected and may have varying depths and consequently varying discharges. If an intake to the recording gauge is located in one of these channels, it will record only the gauge height and accompanying backwater for that channel. If the observer is unaware of the existence of this condition, he may assume that this is the effective gauge height for the complete section, whereas it may be an erroneous reading.

Photograph 3.
Ice nappe over control at gauging station B-1

Surface Ice Layering Effects

Ice layering at both the controlling section and in the weir pond will affect the stage-discharge relationship. In both cases, the effects of water flowing over top of the initial ice layer will not be recorded unless there are holes in the ice connecting the first and second water layers; however, when the water layers are interconnected, the gauge height recorded includes the actual thickness of the initial ice layer, thereby producing a false gauge height. If ice forms on the second water layer, it may act as ordinary surface ice, and as in a single ice-layer system, constrict the total cross-sectional area and produce additional effects on the gauge height.

Frazil Ice Effects

The presence of frazil ice floating in the stream or compacted under or against the surface ice, tends to decrease the effective carrying capacity of the stream channel or the control. If ice build-up occurs in the stream channel, its effects may not be noticeable on the recorded gauge height; however, it may interfere with the taking of discharge measurements. Build up of frazil ice at the control or between the control and the gauge intake, can produce a false gauge height.

Anchor Ice Effects

When anchor ice forms on objects in the streambed, its sponge-like structure may retard water flow through it. This in effect decreases the capacity of the stream channel, resulting in an increase in stage at the point of formation and if the condition is severe enough, a false gauge height reading on the recorder. With the formation of anchor ice downstream of the control, the effective cross-sectional area of the channel will be reduced and sufficient backwater may be produced to cause partial or total submergence of the control. When the anchor ice forms at the control, a direct increase in stage can again result. Like frazil ice, the presence of anchor ice in the stream channel may affect the taking of discharge measurements.

As anchor ice usually forms at night, the backwater produced by it will likely be greatest during the early hours of the day. Because anchor ice does not form under an ice cover, the problems associated with it usually occur during the start of the freeze-up period, until surface ice has formed.

METHODS AND TECHNIQUES OF ICE CORRECTION

In examining the effects of ice formation on streamflow hydraulicas as previously described, it can be seen that all types of ice formation can affect the stage-discharge relationship by altering the stage. This change in stage is usually an increase

due to the constricting effect at the controlling section and/or other changes in hydraulic characteristics of the channel caused by the ice formations.

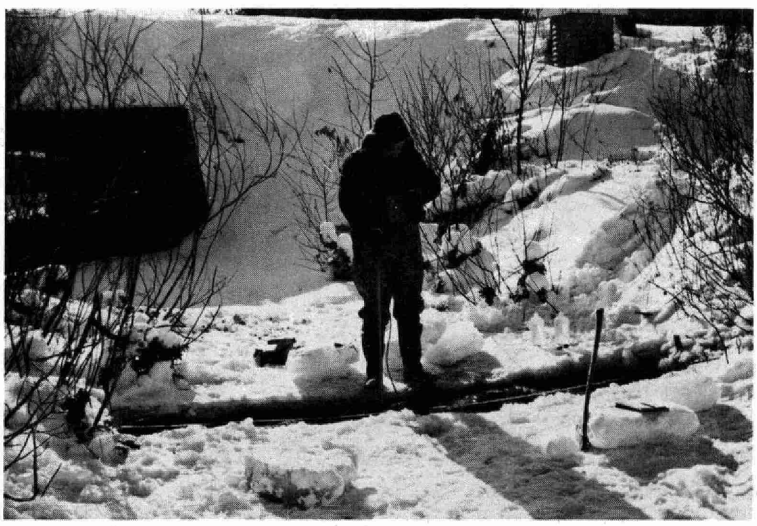
The application of ice corrections, or 'backwater corrections', to attempt to quantify the actual change in stage caused by the ice, requires a thorough operational knowledge of each individual streamflow gauging station. This includes familiarity with the type, condition and location of the controlling section and the ice formations that can occur at the site. With this knowledge and with daily meteorological records of maximum and minimum air temperatures, data on daily precipitation, and actual flow measurements, various techniques for ice corrections can be applied to the ice-affected discharge records.

Discharge Correction Method

Under conditions where significant flow can be found under the surface ice cover, the most common method of arriving at ice corrections involves the measurement of actual discharges at various times during the ice-affected period. These discharges can be used in various ways, in conjunction with the open-water stage-discharge relationship, to correct hydrograph plots of continuous or mean daily ice-affected gauge heights or discharges.

Due to the relatively small stream channels and discharges at the streamflow gauging stations, it may be impossible to obtain accurate discharge measurements under a heavy surface ice cover. Often when a section of heavy ice cover is removed very little clearance is found between the under-surface of the ice and the streambed, thereby making it virtually impossible to obtain accurate depth and velocity readings. A great amount of manpower and time is also required to manually clear a sufficiently large section of heavy ice cover so that stream turbulence is eliminated to allow for a proper discharge measurement.

As an experiment in the IHD representative basins under study, a few discharge measurements were taken during the past winter periods using the method described above (Photograph 4); however, it was found that not enough reliability could be placed on the results in order to use them for accurate ice corrections.

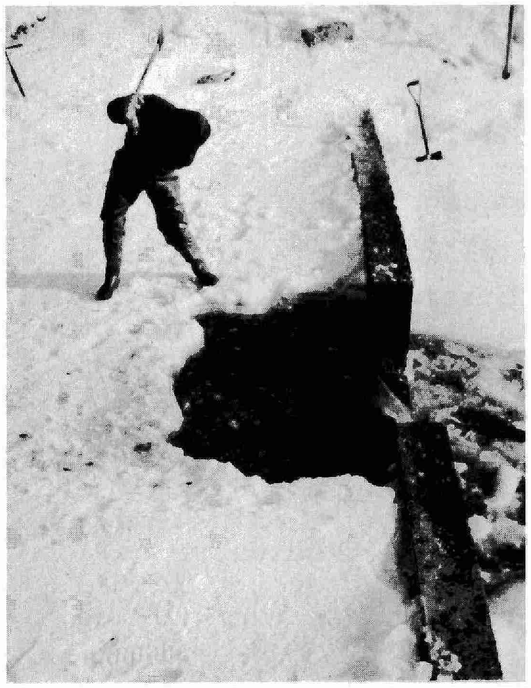


Photograph 4.
Discharge measurement through heavy ice cover at gauging station 5-2

Gauge Height Correction Method

Because of the inability to obtain accurate ice corrections using the discharge correction method at some stations, another method of correcting gauge heights may be used, to allow the application of the open-water stage-discharge relationship.

To obtain the open-water gauge height from an ice-affected gauge height, the ice that is causing the constriction and backwater must be recognized and removed. Surface ice build-up at the control, resulting in backwater generally is the most common cause of false gauge heights. To alleviate the resulting backwater, the ice at the control can be removed manually, usually by chopping the section clear with hand-tools (Photograph 5). As ice is being cleared from these controls, care must be taken not to damage or disturb the control, as the open-water stage-discharge relationship could then be altered. To ensure that open-water conditions remain in effect as long as possible after the control has been cleared, the weir pond and a corresponding area downstream of the control should also be totally cleared of surface ice. This will tend to retard the re-formation of ice at the control.



Photograph 5.
Clearing ice weir pond and control at gauging station 0-4

Once the control is clear of ice it should be noted if any evidence of backwater at the control remains. If the control is partially or totally submerged, the cause may be due to anchor ice or ice jamming in the downstream channel. These ice conditions must be eliminated. To relieve the backwater caused by anchor ice, the porous mass must be detached from the streambed, if possible. In relatively shallow streams this can be accomplished by simply walking through the anchor ice and breaking it up. Care must be taken that the anchor ice which is detached does not jam with surface ice further downstream.

If backwater from jammed floating surface ice is causing submergence of the control, an attempt should be made to eliminate the cause. With large quantities of jammed ice and relatively flat channel slopes, however, all backwater cannot always be totally eliminated.

With the ice conditions causing the false gauge heights removed, open-water conditions will come into effect. The differences between false gauge heights and open-water gauge heights yield gauge height corrections which can be interpolated and applied to the ice-affected records for the period in question.

Interpolated Correction Method

When either the discharge or gauge height correction methods are used, a number of instantaneous correction points are obtained. As the degree of these corrections will not be constant when applied to the periods between the corrections, another method has to be used to interpolate the correction values for these interim periods. This method employs the fact that variations in discharge can often be correlated with variations in air temperature, precipitation and ice formation. The main factor probably is temperature, as it predominantly regulates ice growth.

Before discussing the application of this method of correction, it is necessary to consider the effects on the stream-stage hydrograph of some changing physical conditions at a gauging station. Under general conditions, the amount of backwater due to ice build-up will increase and the discharge will decrease with decreasing temperatures. In examining a period of streamflow record, an indication of backwater due to ice may be evident on the stream-stage hydrograph as a steeper slope of the trace on the falling stage than on the rising stage of the graph. Commonly, in the open-water period, the graphical slope of the rising stage is steeper than that of the falling stage. As an example, this is evident on the stream-stage hydrograph (Figure 1, Appendix B) taken from streamflow gauging station S-2 (Map 2, Appendix B). The trace of the hydrograph on March 25, 26, 27 and April 2, 1970, indicates typical open-water conditions with the slopes of the rising stages being steeper than the slopes of the receding stages. The receding portions of the hydrograph on March 29 at 0800 hours, March 30 at 0830 hours and on March 31 at 0800 hours, probably indicate that the control was not operating under natural open-water conditions. The receding slopes of the hydrographs in these cases are steeper than the rising slopes. The prevailing below-freezing temperatures support the fact that the increases in gauge heights were caused by ice formations, rather than by possible increases in runoff.

Ice effects on the hydrograph may at times show as sharp, erratic fluctuations of very small amplitude. These, however, may not always be indicative of backwater where an ice correction should be applied, as they may be of insignificant magnitude.

With a sudden and extreme drop in temperature, a stream-stage hydrograph may show a sharp decrease in gauge height. This may be due to a corresponding decrease in ground-water discharge (baseflow) into the stream, likely caused by partial freezing of the streambanks. Such storage accumulated in the banks would likely be released into the stream as increased baseflow when temperatures rise. With decreasing temperatures, some of the decreasing streamflow observed may be attributed to water being taken into storage as ice in the channel.

A sharp decrease in stage may also be due to ice jamming upstream of a station, resulting in channel storage and decreased downstream flow. Consequently, when the water that was retained is released or the channel storage is exceeded, there can be a quick recovery of the water-level stage comparable to that under open-water conditions, and usually to a stage above-normal open-water conditions, even though air temperatures may remain below freezing. It should also be pointed out that an above-normal open-water condition of gauge height, as recorded on the hydrograph, may also be partially caused by backwater from an ice-constricted control.

As the flow gradually stabilizes to the stage where there appears to be no backwater at the control, the low point on the hydrograph can usually be considered as minimum flow or baseflow conditions for the period. This provides one other point of true gauge height to which ice-affected gauge heights can be interpolated and corrected.

During the winter period, the major portion of all streamflow is received directly from ground-water discharge. As the lower baseflows for the year generally occur during the period of September-October, the baseflow values during this period can also be used as approximate guidelines for determining baseflow during the ice-affected periods. During periods between points of corrected gauge heights, if there is no direct surface runoff, (i.e. below-freezing temperatures and no rainfall), the flow can be interpolated as being totally baseflow.

Keeping in mind the conditions described above, and using data on air temperature, precipitation and ice-formation records, with the occasional total gauge height correction determined through ice clearing, ice corrections can be interpolated and applied to arrive at reasonably accurate winter streamflow records. The accuracy will depend upon the frequency of total ice corrections obtained in the field and their proper application to the hydrograph under the various ice conditions encountered.

CASE STUDIES - Ice Formation Effects on the Stream-stage Hydrograph and Consequent Corrections

In correcting the ice-affected records for the streamflow gauging stations under study by the Water Resources Branch, the gauge height correction method and the interpolated correction method are applied directly to the actual stream-stage hydrograph. As hourly fluctuations which may be significant in such cases can be taken into direct consideration and considering the small flows encountered, these appear to be the most accurate techniques. As ice formations and the accompanying false gauge heights are never constant for an extended period of time, and as the actual true gauge heights are obtained only occasionally in the field,

the ice corrections that are applied using the interpolated correction method can only be considered as estimates. The following case descriptions, taken from the IHD representative basin streamflow gauging station network, illustrate the false gauge height hydrographs as produced by the various ice forms, and the corresponding corrections applied.

Surface Ice Corrections

1. A simple, accurate surface ice correction is illustrated at streamflow gauging station B-1 (Map 2, Appendix A) for the period of January 27-30, 1969 (Figure 2, Appendix B). Corrections of gauge height obtained in the field at this station can be taken as quite reliable, as the broad-crested, concrete control is heated, thereby preventing any ice from adhering strongly to the control and allowing for easy ice clearing. This ensures that all backwater caused by constriction at the control can be easily eliminated.

Following a mild period ending on January 24, with the subsequent decrease in temperature, the natural flow due to runoff began to taper off. On January 27, the stage increased for no apparent reason. A field observation and subsequent gauge height correction obtained by clearing ice from the control, showed that the increase was due to ice build-up at the control (Photograph 6). On January 28-29, the control again appeared partially blocked, probably due to ice forming with the lowered temperatures. A straight line, approximately representing the baseflow evident on January 23, was used to apply the ice correction for this period. The increase in temperature and the precipitation on January 29-30 produced a natural increase in streamflow as is indicated by the change in the expected slope of the descending stage of the hydrograph. The small erratic fluctuations from 2330 hours on January 29 to 1200 hours on January 30 probably indicate, that although there was a natural increase in streamflow, the gauge height was still being affected by ice. An ice correction was applied to take this into consideration.

Photograph 6.
Surface ice formation at gauging station B-1, looking upstream

2. The presence of ice at the controlling section is not always an indication that an ice correction will have to be made to the recorded hydrograph. This is evident from the records at streamflow gauging station W-3 (Map 2, Appendix A), for the observation on December 28, 1970 (Figure 3, Appendix B). When the ice cover that was completely covering the control was cleared (Ice Sheet 1, Appendix C), no change in gauge height occurred; therefore, no correction was necessary. The ice sheet (observation of ice condition) indicated that the ice was completely bridging the flow but it was observed that the flow was not constricted. The increase in stage from December 21-23, however, was not likely caused by an increase in natural streamflow, as confirmed by the meteorological data (i.e. temperature below freezing and negligible precipitation). The increase may have been due to the initial formation of the ice conditions that were observed and cleared on December 28.

   The sharp decrease in flow recorded on December 18 was probably due to accumulated channel storage upstream of the recording station, perhaps as a result of ice jamming. The subsequent rise in stage was then due to release of the water held in storage. The flow at this time was not significantly affected by ice, as the center of the control, which contained the low flows, was observed to be free of ice (Ice Sheet 2, Appendix C).

   The sharp decrease in flow on December 21 was likely due to retention of ground-water flow in the streambanks caused by the decrease in temperature. This phenomenon can be verified as a decrease in baseflow as similar sharp decreases in gauge height were also recorded at streamflow gauging stations W-4, W-2 and S-3 (Map 2, Appendix A).

3. Records from streamflow gauging stations S-3 (Map 2, Appendix A), from December 29, 1967 to January 23, 1968, (figures 4a, 4b, and 4c, Appendix B) show the interpolation and application of ice corrections over a long period of time, using meteorological data and observations of ice formation, to obtain the final total corrections. On December 29, a sudden increase in stage occurred as the ice was cleared from the weir pond (Ice Sheet 3, Appendix C) and became caught on the control; it was not removed and thus produced backwater.

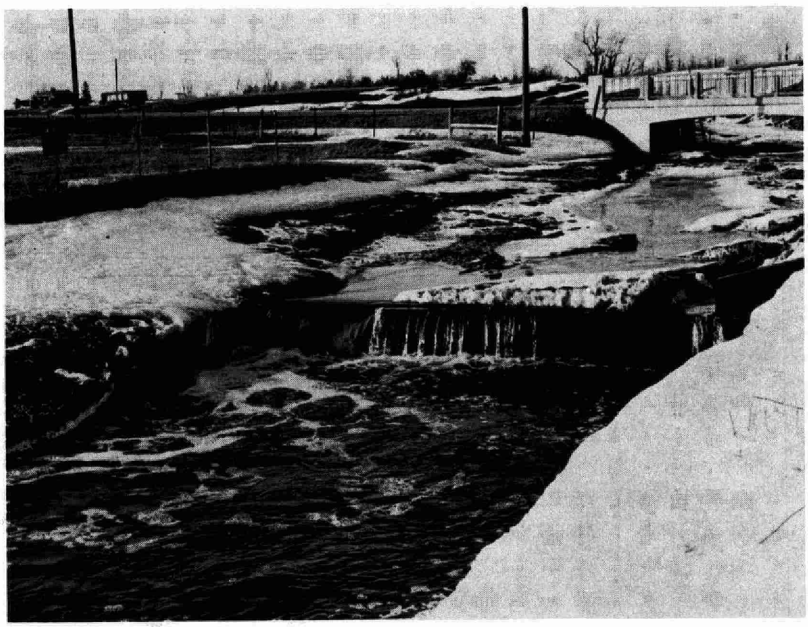
   The rapid decrease in stage on January 1 corresponds to a sharp drop in temperature during the night, resulting in a significant decrease of flow. The subsequent recovery of the hydrograph must be dampened by applying an ice correction to take into consideration the fact that there was ice on the controlling section, as indicated by the descending portion of the hydrograph being steeper than the ascending portion. As can be seen from ice sheets 4-6, Appendix C, the surface ice formation at the controlling section covered a progressively larger area as temperatures continued below freezing. This resulted in progressively larger amounts of backwater being produced, as is evident by the rising peaks of the erratically fluctuating hydrograph until January 16.

   On January 1, 5, 7, and 8, the water level is considered to have dropped to the point where the normal open-water cross-sectional area of the control was no longer constricted by the ice formation. These decreases in stage are considered to have been due to decreases in ground-water inflow to the stream. Similar decreases in stage

were recorded at nearby streamflow gauging stations S-2 and B-4 (Map 2, Appendix A) on the same dates. The low-flow points on the hydrograph for these dates are considered as being under open-water flow conditions and were used to apply ice corrections to the adjacent ice-affected records. All interpolated ice corrections applied between these points and the total correction obtained by clearing the ice from the control (Ice Sheet 7, Appendix C) on January 18, can be considered to yield estimates of the winter baseflow. The small, sharp, erratic fluctuations recorded during parts of this period also indicate that ice was forming at the controlling section.

The gauge height correction obtained by clearing the surface ice from the controlling section (Ice Sheet 7, Appendix C) on January 18, (Figure 4c, Appendix B) is representative of a typical, surface ice correction. When the ice was cleared from the pond it floated downstream and jammed on the control. The resulting backwater is indicated on the hydrograph as the instantaneous increase in the gauge height; this was immediately relieved by removing the jammed ice from the control and a total correction was obtained. The same type of effect could result if the ice jamming occurred downstream of the control, causing submergence of the control. The erratic fluctuations on January 18 and 19 indicate that ice was re-forming on the control, but was of insufficient magnitude to produce a false gauge height.

4. Photograph 7 of gauging station 0-4 (Map 3, Appendix A) illustrates the effect of surface ice during the spring breakup. The surface ice that was floating in the weir pond became caught on the control. This produced a false gauge height as the open-water cross-sectional area of the control was reduced. As a gauge height correction was not obtained during the observation, the magnitude of the ice correction had to be interpolated from adjoining portions of the hydrograph record.



Photograph 7.
Surface ice caught on the control during spring break-up at gauging station 0-4

The methods of interpretation and application of ice corrections previously described are typical of those applied to correct false gauge heights caused by surface ice formations at various controlling sections.

Siphon Corrections

The typical effect of siphon action on the stream-stage hydrograph was previously explained under the heading 'Effects of Ice on the Stage-Discharge Relationship'. At station B-1 during the period from January 7-11, 1968, (Figure 5, Appendix B), the ice correction can be assumed to be a straight line correction. Because of the continuous below-freezing temperatures there was no increase in flow. The corrected flow is approximately equal to the winter baseflow as illustrated by the constant stream-stage hydrograph prior to the start of siphon action.

The siphon action always appears to work on the principle previously explained, but the corrections obtained by manually clearing ice from the control are not always consistent. Various siphon effects and the consequent corrections are shown by the following examples taken from several streamflow gauging stations in the IHD representative basins.

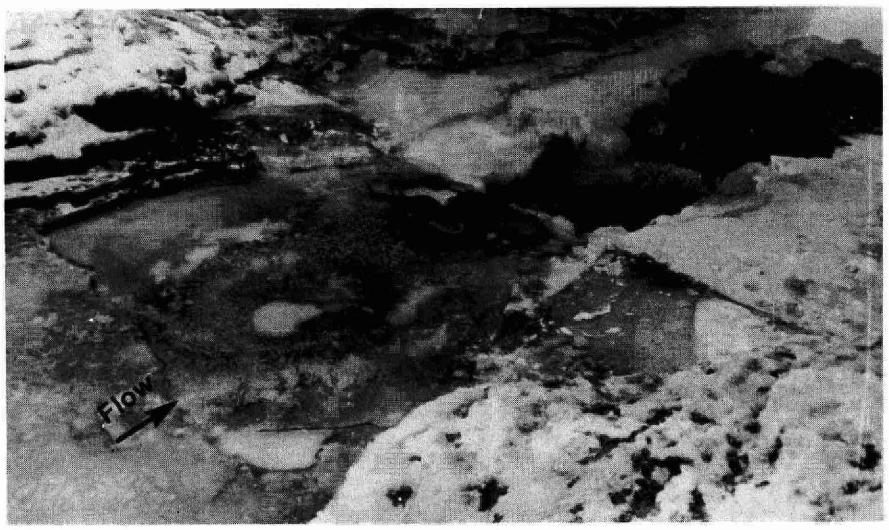
1. At gauging station B-1, the siphon effect was again produced during the period February 11-14, 1968 (Figure 6, Appendix B). The effect of this siphon, however, contrasts with that of January 8-9 (Figure 5, Appendix B), as the minimum siphon effect occurred at the start and increased in amplitude as the thickness of the ice nappe increased. This record indicates that a single siphon cycle can remain in effect over varying lengths of time, as indicated by the continuous fluctuations on February 11-12, the 15-30 minute durations between cycles during February 12, the 10-hour duration during February 12-13 and the 17-hour duration during February 13-14. When a site observation was made on February 14, the siphon was in effect but with the clearing of ice from the control (Ice Sheet 8, Appendix C), the open-water stage for that discharge was obtained. During the period February 10-14, all temperatures were below freezing and as the baseflow following the clearing of the control on February 14 remained constant, it can be assumed that the baseflow was also constant during the siphon period.

   When the correction was obtained on February 14, the occurrence of a siphon was verified as the water level in the weir pond had been below that for baseflow during open-water conditions. The fact that the gauge height was recorded above the actual open-water stage verifies the fact that the siphon effect was caused by water pressure

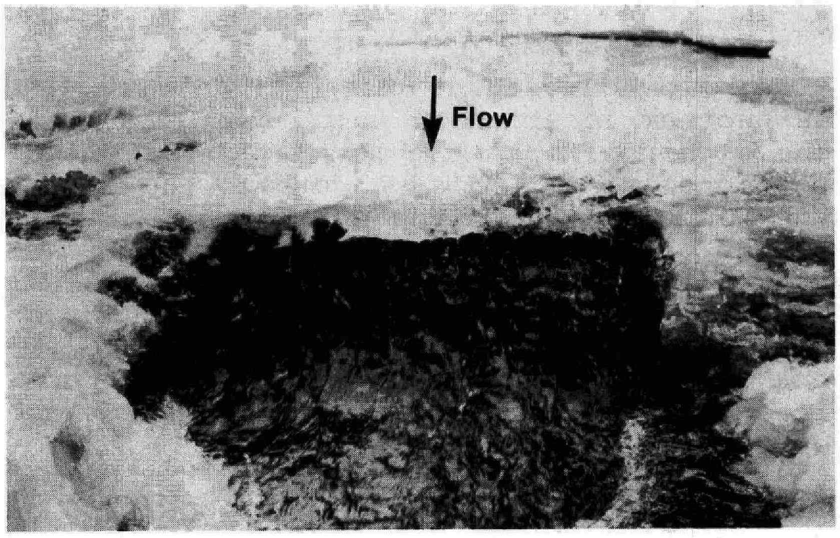
build-up in the weir pond, probably due to constriction of the area at the control.

2. Streamflow gauging station W-3 (Location Map 2, Appendix A) is another location at which siphon action has been observed. The siphon effect at this station extended over a long period of time. This was due to the fact that the ice adhered directly to the non-heated, broad-crested, concrete-capped gabion control. The amount of freefall over the control was such that it lent itself readily to ice-bridging over the control and the formation of an ice nappe. The ice-constricted area at the control did not appear to change rapidly with changes in temperature, therefore the ice cover was retained and able to grow over a long period of time.

The ice effects at station W-3 from December 22, 1969 to January 7, 1970 (figures 7a and 7b, Appendix B) began as typical surface ice formation effects and appropriate corrections were applied. The siphon effect started on December 25 and continued until a correction was obtained on January 7, by clearing the ice from the control (Photograph 8 and Ice Sheet 9, Appendix C). After the siphon started, it continued in the same manner until January 1, when the amplitude of its fluctuations decreased somewhat. As below-freezing temperatures continued, the cross-sectional area at the control probably decreased with the increase in thickness of the ice nappe and the ice adhering to the control. Assuming that the flow remained fairly constant during the siphon period, the flow velocity over the control probably increased as the area at the control gradually decreased with the constricting ice build-up . As the flow velocity increased, coupled with the increased ice nappe thickness, there was a gradual decrease in the stage at which the siphon cycle began. Photograph 9 was taken after the ice nappe over the control was cleared. It shows the remaining ice adhering directly to the control, constricting the width of the flow over the control.



Photograph 8.
Surface ice cover and nappe over control at gauging station W-3



Photograph 9.
Taken after the ice nappe in Photograph 8 was cleared. Shows ice adhering directly to the control, constricting the width of flow

After January 2, the siphon action was occurring without the evidence of backwater, as is shown by the hydrograph from January 2-7, where the start of the siphon effect is recorded below the estimated baseflow level. All of the continuous fluctuations during this period were caused by siphon action, as verified by the elimination of the effect when the ice was cleared from the control on January 7, returning the level back to that of open-water conditions. After the control was cleared, open-water conditions prevailed only for 24 hours before effects of ice formation were again evident. Backwater was then produced by surface ice which again resulted in siphon action on January 10. It is likely that the continued below-freezing temperatures prevented any significant increase in surface runoff during the affected period. As the total correction obtained on January 7 indicated winter baseflow conditions, an approximating straight-line ice correction can be applied to the siphon action periods, both before and after the observed correction on January 7.

3. Records from streamflow gauging station S-2 (Map 2, Appendix A) from January 13-21, 1970 (Figure 8, Appendix B) show both surface ice and siphon effects. At the observation on January 21, a siphon action appeared to be in effect; however, when the ice that was covering the weir pond and bridging the control was cleared, (Ice Sheet 10, Appendix C) the natural flow conditions were resumed at the lower gauge height of the siphon cycle. As the water level had not drawn down below that of the open-water condition during the siphon cycle, it would tend to indicate that a full siphon had not been in effect. At the time of the observation on January 21, the siphon action had appeared to have reached the point where the cycles were completely counteracting the backwater but were not siphoning the water level below the natural flow stage. Perhaps air began to enter the system before the open-water gauge height was reached. The amplitude of this backwater siphon increased in magnitude, perhaps as the air source was eliminated with continued ice build-up as the air temperatures remained below freezing.

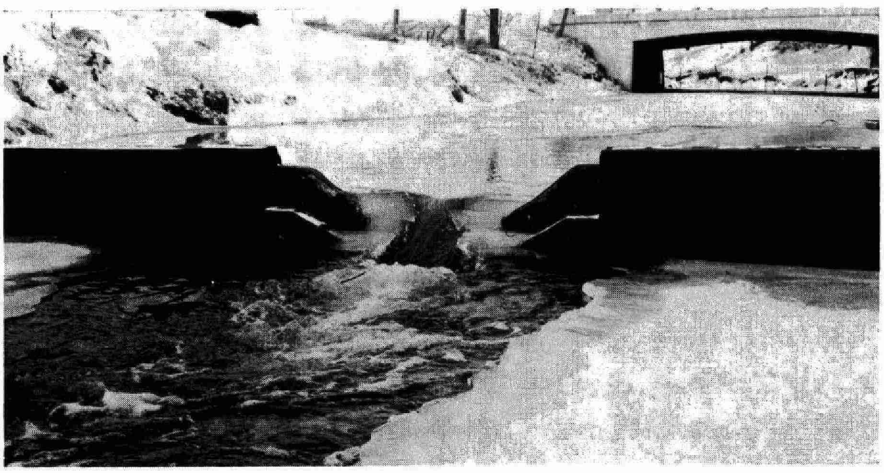
Using the correction obtained on January 21 as a guideline, the low point on the hydrograph from 2000 hours on January 19, to 0100 hours on January 20, can be assumed to be under open-water conditions and was therefore used as a reference to which adjacent ice corrections were adjusted. With the decrease in temperature on January 14 and 19, the baseflow is assumed to have decreased, with the water level falling below the surface ice and creating open-water conditions. This baseflow decrease is verified by similar decreases at streamflow gauging stations S-3 and B-4 (Map 2, Appendix A). Using these three points (January 14, January 19, January 21) of open-water conditions, taking into account the fact that there were insufficient increases in temperature to produce surface runoff, straight line corrections were applied between the individual open-water points.

The preceding examples of siphon effects indicate that they do not always have the same effect on the hydrograph with respect to the normal level of natural open-water conditions. Past records also show that no one station consistently shows the same trend in siphon action.

Ice Jamming Corrections

As observed at streamflow gauging station 0-4 (Map 3, Appendix A) on February 23, 1970 (Figure 9, Appendix B), the water level on the downstream side of the control was backed up, rising approximately three feet above normal as a result of downstream ice jamming, causing complete submergence of the control (Ice Sheet 11, Appendix C). Photograph 10 shows a similar situation but with only partial submergence of the control. As the downstream channel was completely blocked, it was impossible to entirely alleviate the backwater problem. The correction in gauge height on February 22 was made when the observer cleared the ice from the notch of the control. A partial correction was obtained on February 23 by manually clearing some of the jammed ice, but the backwater problem very quickly returned. Observations on February 24 and 27 indicated that backwater was still present.

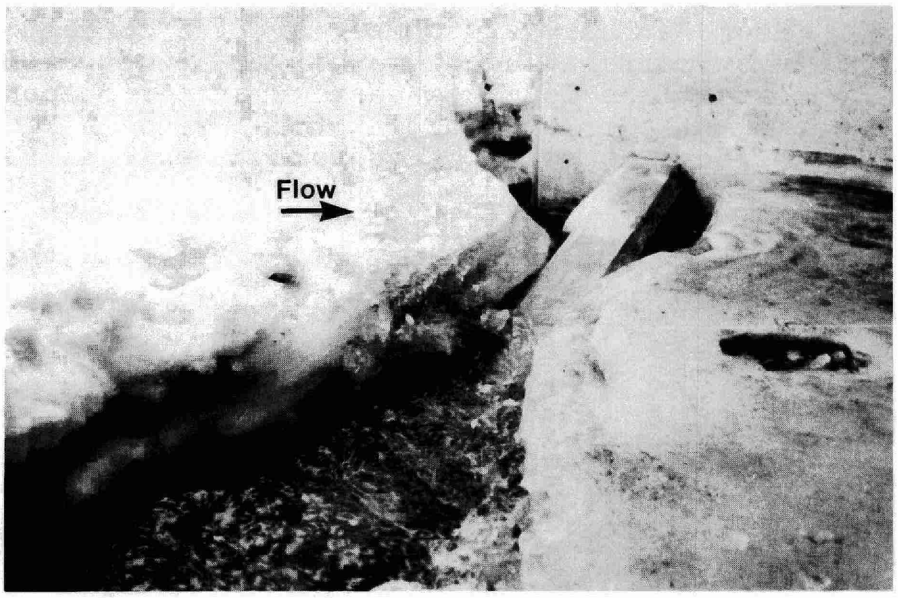
From February 22 to March 1, ice corrections were applied mainly by correlating gauge height fluctuations with air temperatures. Ice corrections for this particular period can only be classified as being of poor quality, as total gauge height corrections to which ice corrections could be adjusted, could not be obtained throughout the period.



Photograph 10.
Backwater causing partial submergence of the control at gauging station 0-4

Ice Channelling Corrections

1. At streamflow gauging station B-3 (Map 2, Appendix A), false gauge heights have been produced by the formation of ice channels in the weir pond. Here, due to flow disturbance caused by an upstream mill, the underside of the ice cover forms unevenly, perhaps as a result of the water-level fluctuations due to mill operations. Separated flow channels are also produced, as observed on January 4 and 13, 1971 (ice sheets 12 and 13, Appendix C). At both observations, the staff-gauge readings in the weir pond were lower than those recorded in the gauge house. The staff gauge is located two feet upstream and to the left of the control and during these observations was free of surface ice cover. When the surface ice was cleared from the weir pond during the observation on January 13 (Ice Sheet 13, Appendix C), the intake to the stilling well was found to be located in the ice-divided flow channel on the left side of the stream. After the ice was cleared, the gauge height in the gauge house dropped while the outside reading at the staff gauge, which was always in an open-water area at the control, did not change. This indicated that the ice-separated flow channels had been producing a false gauge height at the recording gauge. The readings obtained at the recording gauge after clearing the ice from the weir pond matched those from the staff gauge indicating that when the controlling section is not influenced by ice formations, gauge height readings taken in this area will be comparable to true recording gauge readings. The formation of thick surface ice along with ice channelling in the weir pond appear to have caused increased pressure under the ice, thus affecting recording gauge readings. This pressure build-up is also indicated by the eddies and turbulence of the water as it leaves the ice-covered weir pond, just in front of the control (Photograph 11). The photograph also shows the submergence of the control due to backwater caused by surface ice and jammed ice downstream of the control.



Photograph 11.
Surface ice in weir pond causing increased pressure in weir pond and surface ice downstream of control causing backwater and control submergence

2. While attempting to clear a section across the stream, ice channelling was also observed at streamflow gauging station 0-3 (Map 3, Appendix A). It is not known, however, if the recorded gauge height at this station was affected by the ice channels, as the thick ice cover, the extensive width of the stream and a natural control have prevented any successful attempt to obtain a corrected gauge height.

Surface Ice Layering Corrections

Surface ice layering has been observed at streamflow gauging station 0-2 (Map 3, Appendix A). Ice layering appears more prevalent at this location than at other streamflow stations under study. This is probably due to the usually heavier build-up of the initial surface ice layer at this station.

During the observation on January 15, 1971 (Figure 10, Appendix B), ice layering was not realized until a hole was chopped through the ice to the streambed near the stilling well intake. At this time, two ice layers with water flowing between them were found to exist (Ice Sheet 14, Appendix C). The intake was located in the water beneath the second ice layer. When the ice was cleared from the immediate area around the staff gauge in the weir pond, the resulting gauge height reading from the water beneath the first ice layer was equal to that recorded inside the gauge house. This agreement indicated that the water between the ice layers was hydraulically connected to the water flowing beneath the initial or bottom ice layer, probably by holes along the streambank. If the water layers had not been hydraulically connected, the two gauge heights would have been different, the inside gauge reading only representing the flow beneath the initial ice layer and the backwater within that system.

The sudden decrease in the gauge height shown on January 15 was probably due to a decrease in ground-water inflow as a result of low temperatures. A similar gauge height decrease is also evident at the upstream gauging station 0-1 (Location Map 3, Appendix A). The low-flow stage at this point was considered not to be directly influenced by ice formation at the station; thus it was assumed that an open-water condition prevailed. As a total ice correction was not obtainable during the observation described above, all ice-corrected gauge heights are estimated according to the assumed low-flow open-water point for January 15, using available meteorological data and estimates of the approximate winter baseflow.

Frazil Ice Corrections

With the rapid formation of surface ice at most of the streamflow gauging stations under study, the formation or presence of frazil ice has never been observed. For this

reason, a detailed description or case history of its effect on a stage-discharge relationship and consequent correction cannot be given.

Anchor Ice Corrections

1. Anchor ice has been observed to form in the stream channel at streamflow gauging station B-3 (Map 2, Appendix A), mainly in the downstream channel where it has produced sufficient backwater to cause submergence of the control. By removing the anchor ice, gauge height corrections of up to 0.55 feet have been obtained.

   Anchor ice has been observed to re-form overnight to again cause re-submergence of the control.

2. The formation of anchor ice has also been observed at streamflow gauging station W-2 (Map 2, Appendix A). At this location, anchor ice did not form in the stream channel, but only on the control. The control is constructed of rock-filled gabion baskets which provide a rough surface, resulting in sufficient turbulence to cause anchor ice formation. Due to the high velocity of the flow over the control, surface ice generally does not form.

Anchor ice formation (Ice Sheet 15, Appendix C) was observed at station W-2 on December 28, 1970 (Figure 11, Appendix B). It re-formed immediately after the control was cleared on that date and subsequently varied in magnitude with complementary changes in air temperature.

The smaller more consistent amounts of backwater shown on the hydrograph from December 24-27, were likely due to heavy anchor ice formation at the ends of the control structure, causing nearly complete obstruction of flow in these areas. The larger, more erratic amounts of backwater indicated on December 28, were caused by anchor ice formation in the center of the control through which the major portion of the flow passes. On January 2, 1971, the natural release of the major portion of the anchor ice occurred when the air temperature increased to a point above freezing.

Ice corrections at this station can be considered to be very accurate as the various gauge height fluctuations can be compared and related directly to those of the upstream gauging station W-1 (Map 2, Appendix A), which remains under open-water conditions throughout the winter period.

The preceding examples cover the most common effects of the various ice formations on streamflow hydrographs. The ice corrections applied employ typical methods to adjust ice-affected gauge heights to open-water conditions. As each type of ice formation does not always produce the same

effect on the streamflow hydrograph, the previous examples of ice corrections can only be used as guidelines for the interpretation of winter streamflow records.

ICE PREVENTION

As ice formations at gauging sites strongly influence the recording of streamflow data, their minimization and prevention or reduction of their effect can substantially reduce the data errors introduced during winter periods. There are several precautions that should be taken in the selection of potential gauging sites and in the construction of stations, in an attempt to minimize or prevent ice formations.

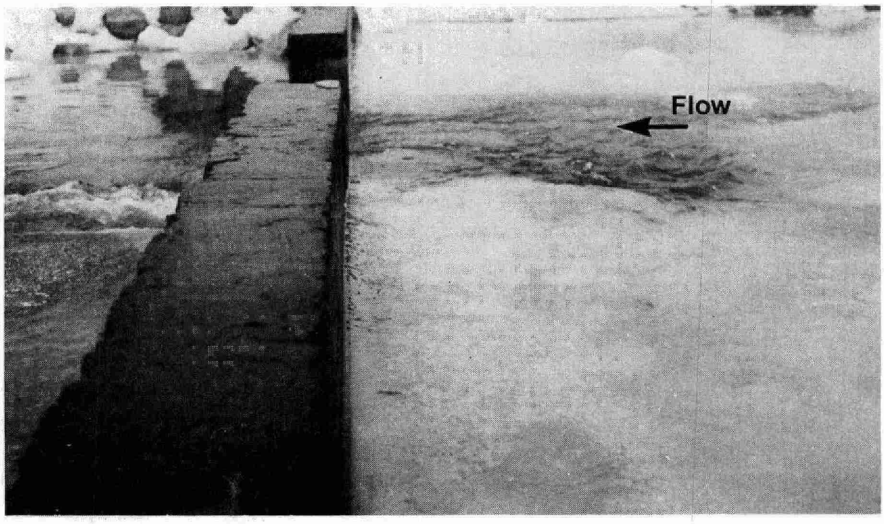
Selection of Site and Control Structure Characteristics

In order to minimize the formation of ice at a streamflow gauging station, the selection of the gauging station site should be made and the station itself should be designed so as to be the least conducive as possible to ice formation. As the controlling section and both the upstream and downstream areas of the stream channel should be kept as free of ice as possible, the station should be constructed at a location where the controlling section will receive the maximum available sunlight; this effect will tend to retard initial ice formation and will also accelerate the rate of any ice break-up. If possible, the ideal station location should have an unobstructed, uniform channel downstream of the controlling section; ice jams are thereby prevented, eliminating backwater over the control. In choosing the location for a station for which an artificial control is to be designed, it should also be kept in mind that fast flow velocities hinder ice formation. For this reason, controls should be of the sharp-crested V-notch or rectangular type, rather than of a low or broad-crested design; they should also have adequate free-fall to reduce the chance of backwater submerging the control.

During the construction of some of the IHD streamflow gauging stations, electric heating cables were installed directly into artificial controls. In all cases where heating cables were incorporated into the design, the controls were of the broad-crested, concrete type. The heating cables were installed approximately two inches below the surface of the concrete and were placed so as to provide maximum heat at those areas where the ice would likely be in contact with the control. This method did not prove entirely satisfactory. Although the heat provided by the heating cable was sufficient to prevent the ice from adhering directly to the controls, it did not prevent ice from bridging over the controls. The benefit thus derived from the use of incorporated heating cables is that the ice can be removed with relative ease to obtain a corrected gauge height. At stations with non-heated

controls, ice does not become detached from controls until temperatures are favourable and increased streamflows can cause pressure build-ups under the ice in the weir ponds, thereby affecting gauge heights.

To delay ice formation and to reduce the length of time that the ice remains attached to the control, the artificial controls that are directly exposed to sunlight were painted with a black enamel, consisting of a modified chlorinated rubber base, resistant to moisture, fungi growth, alkalis and acids. The black-painted surface of the control increases the amount of solar radiation that is absorbed by the control structure. This was found to decrease the length of time that the ice remained attached to the controls during the spring break-up. Photograph No. 12 of streamflow gauging station 0-4 (Map 3, Appendix A) shows the effects of the black surface of the control on the ice in the weir pond. The heat absorbed by the control was sufficient to melt the ice that had been adhering directly onto the surface of the control. Under normal conditions, with no black paint, this ice could not likely have become detached until some time after the streamflow had significantly increased, with increasing temperatures. The control at 0-4 was initially operated without the black paint and significant problems in clearing ice from the control were experienced. Photograph #7, page 17, shows the ice floating free of the control when the streamflow increased.



Photograph 12.
Black surface of control at gauging station 0-4 absorbs sufficient heat to keep ice from adhering to control

Ice Prevention in the Stream Channel

In an attempt to arrive at effective techniques for the prevention of ice formation in stream channels, various possible solutions were considered in detail. The problem was to design suitable equipment that could be used to keep ice from forming and/or to reduce the time required to clear ice from a given section. Various ideas that could be used for ice prevention and clearing were considered; however, due to the limitations of water depth and the quantity of discharge involved with the streams under study, they did not appear feasible. The following were the main ideas reviewed and the reasoning for their rejection:

a) Air bubbling system:

An air bubbling system in a weir pond upstream of a control would not likely keep a section open as an approximate minimum depth of eight feet of water is required to produce convectional overturn of warm water from the bottom of the weir pond. With shallow depths considered, it was suggested that a heat source be located beside the air bubbler system to provide the required heat. This would prove uneconomical, however, as the continuously moving water would require a very large quantity of heat to sufficiently increase the water temperature to prevent freezing.

b) Floating heating carpet:

A heating carpet constructed of a grid-work of 1/4-inch diameter heating cables, covered with an asbestos and vinyl air mat was also suggested. This ida was rejected for various reasons, the major one being that a very small grid network of heating cables would be required to completely melt the ice. This would prove very costly in construction and in the amount of electrical power required for efficient operation.

c) Inflatable cylinder:

The use of a large-diameter inflatable cylinder that would span the stream was considered. If it were secured in a manner such that the lower half of it would be in the water, surface ice would be prevented from forming in that area of the stream cross-section. After the surface ice cover had formed, above and below the cylinder, the cylinder would be deflated and removed and a streamflow current meter could be inserted into the water in the open section to obtain a discharge measurement. This method of ice prevention was also rejected as the flow in the relatively shallow streams would be completely blocked off by the cylinder, creating further problems.

All proposed methods of clearing ice, or of keeping a section of the stream clear of ice, appear to have disadvantages, largely as a result of the shallow depths, small flows and uniform water temperatures which would require large amounts of heat to prevent ice formation.

Ice Prevention in the Gauge-House Stilling Well and Intake Pipe

Whereas ice formations in the weir pond, at the control or in the stream channel may produce inaccurate records, ice formations in the gauge-house stilling well or the intake pipe to the stilling well result in the actual loss of records.

When a float-activated stage-recorder is set on a stilling well, ice must be prevented from forming in the well so that the float can move freely with the corresponding fluctuations of the stream water level. Several methods can be used to prevent ice from forming in this area. If possible, the stilling well should be installed so that the water level in the well is below the frost line in the streambank. Additional protection against freezing in the stilling well may be gained by the use of a sub-floor, or frost barrier, by the use of oil and/or by the use of an external heat source.

The use of a sub-floor or frost barrier placed in the stilling well, between the main floor of the recorder shelter and the water level, reduces the loss of heat from the well, preserving the natural heat from the surrounding streambank and to some extent the heat of the water, to prevent ice formation. The sub-floor should be placed below the frost line, but should not interfere with the normal fluctuations of the recorder float.

The addition of several gallons of oil in the stilling well may sufficiently suppress the water surface to a level below the frost line where it will not freeze. Alternatively, in a large-diameter stilling well, a small-diameter auxiliary pipe containing the oil, can be placed within the stilling well. The auxiliary pipe must be large enough to accommodate the recorder float and must be open at the bottom to provide free access of the water in the stilling well. As the specific gravity of the oil is less than that of water, the surface of the oil in the stilling well, or in the auxiliary tube, will be higher than that of the corresponding water level in the well. Also the float will ride lower in the oil than it would in the water. Consequently, when using oil, the setting of the water-stage recorder must be adjusted to match the corresponding open-water reading obtained via an outside gauge in the weir pond.

The most effective means of preventing ice formation in the stilling well and in the intake pipe is by use of an external heat source. If available, the most effective source of heat is obtained from electric current. For the prevention of ice formation in the stilling well, heat may be provided by space heaters, immersion heating cables or heat bulbs suspended in the stilling well. Various forms of gas heaters can be used where electricity is not available.

At the IHD streamflow gauging stations under study, immersed electric heating cables are used to prevent ice formation in the stilling wells and in the intake pipes leading to the weir ponds. At most installations, two sets of heating cables are used; one is suspended directly into the water in the stilling well and the other is installed inside the intake pipe to a distance approximately two inches from its end in the stream. This type of installation has been found very successful in eliminating all freezing problems in stilling wells and in intake pipes.

CONCLUSIONS

Due to varying forms of ice formations, the winter period is recognized as the season for which streamflow discharge records usually have a low degree of reliability. To increase the accuracy of the final interpreted records for this period, it is necessary to apply corrections to the ice-affected discharge records obtained in the field.

The application of ice corrections requires a thorough understanding of the effects that the various ice formations have upon open-water stage-discharge relationships. This understanding, together with the knowledge of characteristics of the controls, their locations and the ice formations that are common to the different streamflow gauging stations, can be used to provide reasonably accurate winter discharge records. The accuracy of the winter records also depends on the number of field observations made to obtain a corrected gauge height or a discharge measurement, or simply to obtain information on the existing ice formation.

Using the information on the operating conditions of the individual streamflow gauging stations and the ice formations associated with them, the examples of ice formation effects on the stream-stage hydrograph and the consequent corrections can be used as guidelines by which ice-affected stage records can be corrected to allow the use of the open-water stage-discharge relationships.

There does not appear to be a ready solution to the problems of ice prevention or ice clearing in streams with shallow depths, low water velocities and low winter discharges. Specific criteria for station site and control selection relative to winter operations should therefore be followed closely when planning a streamflow gauging station network.

SELECTED REFERENCES

1. Bilozor, W., 1971. Application of Single-Velocity Method of Measuring Discharge under Backwater Conditions, Internal Circulation, Department of the Environment, Inland Waters Branch, Water Survey of Canada.

2. Corbett, D. M., et al., 1943, reprinted 1962. Stream Gauging Procedures, A Manual Describing Methods and Practices of the Geological Survey; U. S. Geological Survey Water Supply Paper 888.

3. Grover, N. C., and Harrington, A. W., 1966. Streamflow Measurements, Records and Their Uses; Dover Publications.

4. Hoyt, W. G., 1913. The Effects of Ice on Streamflow; U. S. Geological Survey Water Supply Paper 337.

5. Manual of Office Procedures for Computation and Publication of Hydrometric Survey Data; Department of Northern Affairs and Natural Resources, Water Resources Branch, 1962.

6. Selected Techniques in Water Resources Investigations; 1966-67, U. S. Geological Survey Water Supply Paper 1892, 1969.

7. Some Problems of Typology and Classification of Ice Cover on Lakes and Reservoirs; Soviet Hydrology Selected Papers, 1964.

8. Stream-Gauging Stations for Research on Small Watersheds; U. S. Department of Agriculture, Forest Service, Agriculture Handbook No. 268, 1964.

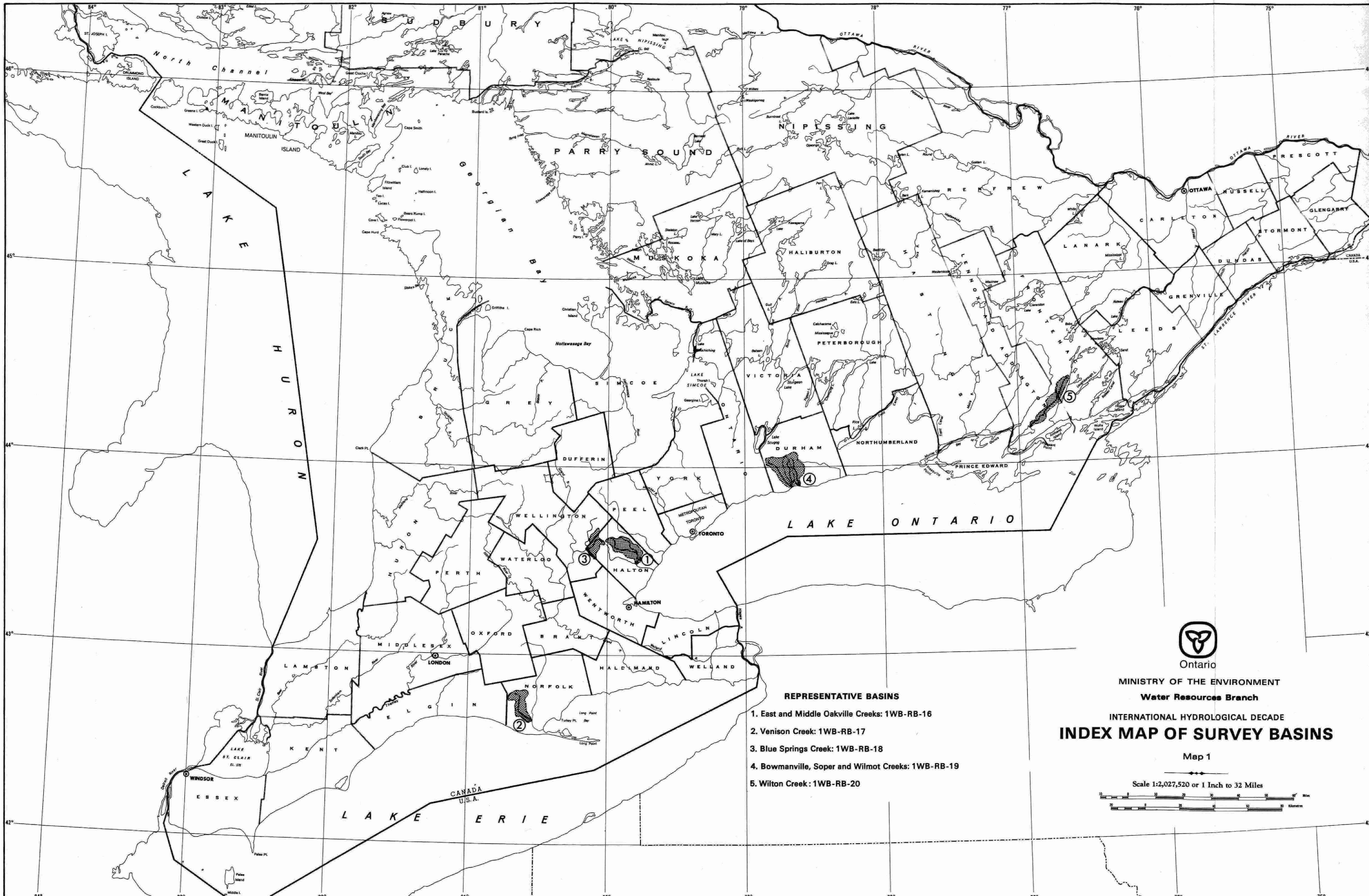
9. Strilaeff, P. W. and Wedel, J. H., 1970. Measurement of Discharge under Ice Cover, Technical Bulletin 29, Department of Energy, Mines & Resources, Inland Waters Branch.

10. Williams, G. P., 1959. Frazil Ice, A Review of its Properties with a Selected Bibliography; Technical Paper No. 81, Division of Building Research, National Research Council.

11. Williams, G. P., March, 1961. Winter Water Temperatures and Ice Prevention by Air Bubbling; The Engineering Journal.

APPENDIX A

LOCATION MAPS


Ontario
MINISTRY OF THE ENVIRONMENT
Water Resources Branch
INTERNATIONAL HYDROLOGICAL DECADE
INDEX MAP OF SURVEY BASINS
Map 1
Scale 1:2,027,520 or 1 Inch to 32 Miles
REPRESENTATIVE BASINS
1. East and Middle Oakville Creeks: 1WB-RB-16
2. Venison Creek: 1WB-RB-17
3. Blue Springs Creek: 1WB-RB-18
4. Bowmanville, Soper and Wilmot Creeks: 1WB-RB-19
5. Wilton Creek: 1WB-RB-20
SUDBURY
North Channel
MANITOULIN
MANITOULIN ISLAND
PARRY SOUND
NIPISSING
RENFREW
Georgian Bay
LAKE HURON
MUSKOKA
HALIBURTON
HASTINGS
LENNOX AND ADDINGTON
FRONTENAC
LANARK
CARLETON
OTTAWA
RUSSELL
PRESCOTT
GLENGARRY
STORMONT
DUNDAS
GRENVILLE
LEEDS
OTTAWA RIVER
ST. LAWRENCE RIVER
PETERBOROUGH
VICTORIA
DURHAM
NORTHUMBERLAND
PRINCE EDWARD
SIMCOE
LAKE SIMCOE
ONTARIO
GREY
BRUCE
DUFFERIN
YORK
PEEL
METROPOLITAN TORONTO
TORONTO
WELLINGTON
HURON
PERTH
WATERLOO
HALTON
HAMILTON
WENTWORTH
LINCOLN
WELLAND
HALDIMAND
BRANT
OXFORD
MIDDLESEX
LONDON
LAMBTON
NORFOLK
ELGIN
KENT
ESSEX
WINDSOR
LAKE ST. CLAIR
LAKE ONTARIO
LAKE ERIE
CANADA
U.S.A.
Nottawasaga Bay
84°
83°
82°
81°
80°
79°
78°
77°
76°
75°
46°
45°
44°
43°
42°

MAP 4002-1

LEGEND

Streamflow Gauging Stations

- **AR** - Artificial control, recording
- **NR** - Natural control, recording
- **NN** - Natural control, non-recording

Meteorological Stations

- **RS** - Standard rain gauge
- **AT** - Air temperature

Ontario

MINISTRY OF THE ENVIRONMENT

Water Resources Branch

INTERNATIONAL HYDROLOGICAL DECADE

BOWMANVILLE, SOPER AND WILMOT CREEKS DRAINAGE BASIN

Map 2

STREAMFLOW GAUGING STATIONS AND ASSOCIATED METEOROLOGICAL STATIONS USED IN ANALYSIS

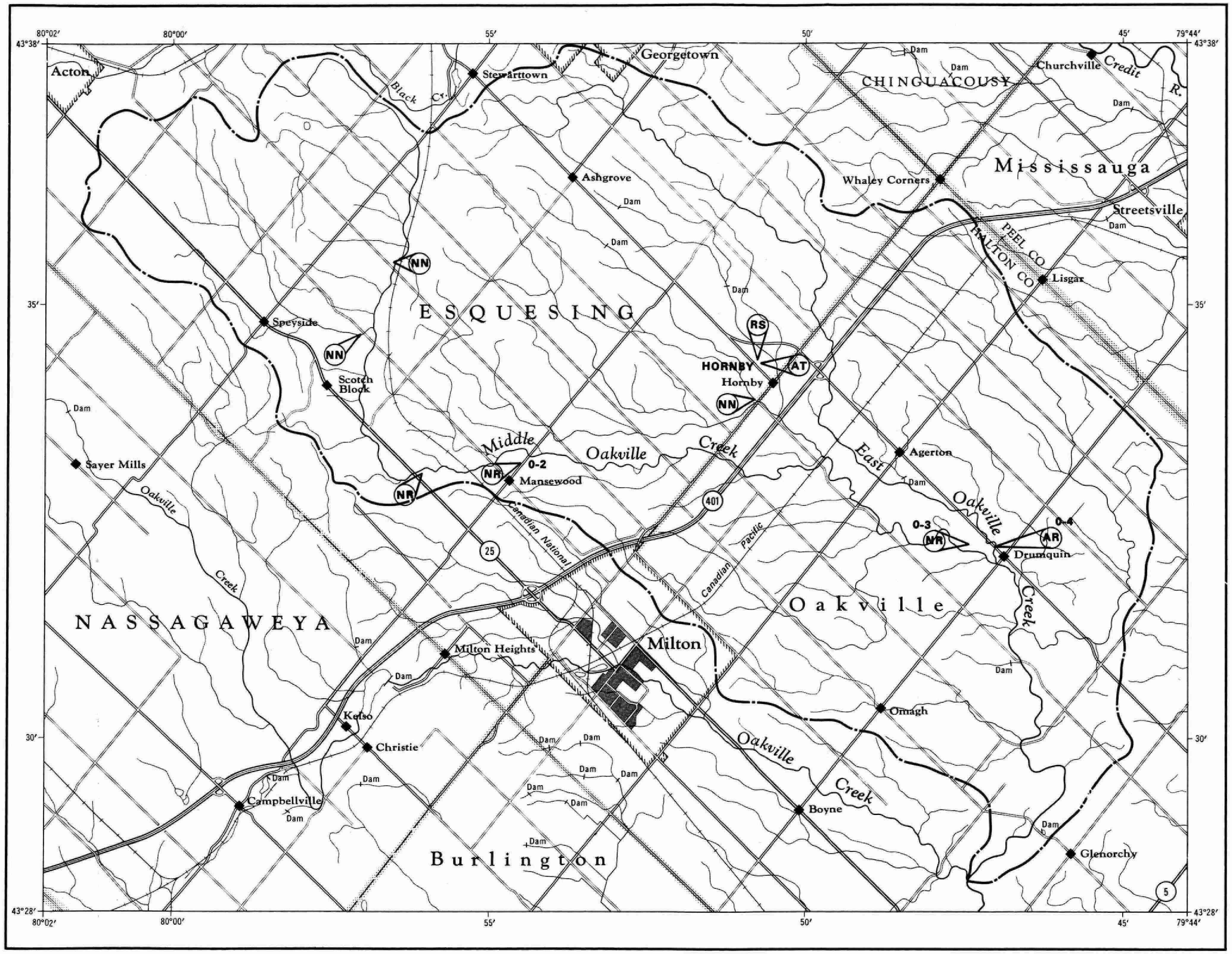
Scale 1:100,000

1 inch equals 1.58 miles

1 0 1 2 3 Miles

1 0 1 2 3 4 5 Kilometres

MAP 2135



LEGEND

Streamflow Gauging Stations

- **AR** – Artificial control, recording
- **NR** – Natural control, recording
- **NN** – Natural control, non-recording

Meteorological Stations

- **RS** – Standard rain gauge
- **AT** – Air temperature

Ontario

MINISTRY OF THE ENVIRONMENT

Water Resources Branch

INTERNATIONAL HYDROLOGICAL DECADE

EAST AND MIDDLE OAKVILLE CREEKS DRAINAGE BASIN

Map 3

STREAMFLOW GAUGING STATIONS AND ASSOCIATED METEOROLOGICAL STATIONS USED IN ANALYSIS

Scale 1:100,000

1 inch equals 1.58 miles

1 0 1 2 3 Miles

1 0 1 2 3 4 5 Kilometres

MAP 2136

APPENDIX B

STREAMFLOW HYDROGRAPHS AND ICE CORRECTIONS

Time Scale 1.2" = 24 hrs

Vert. Scale - as shown

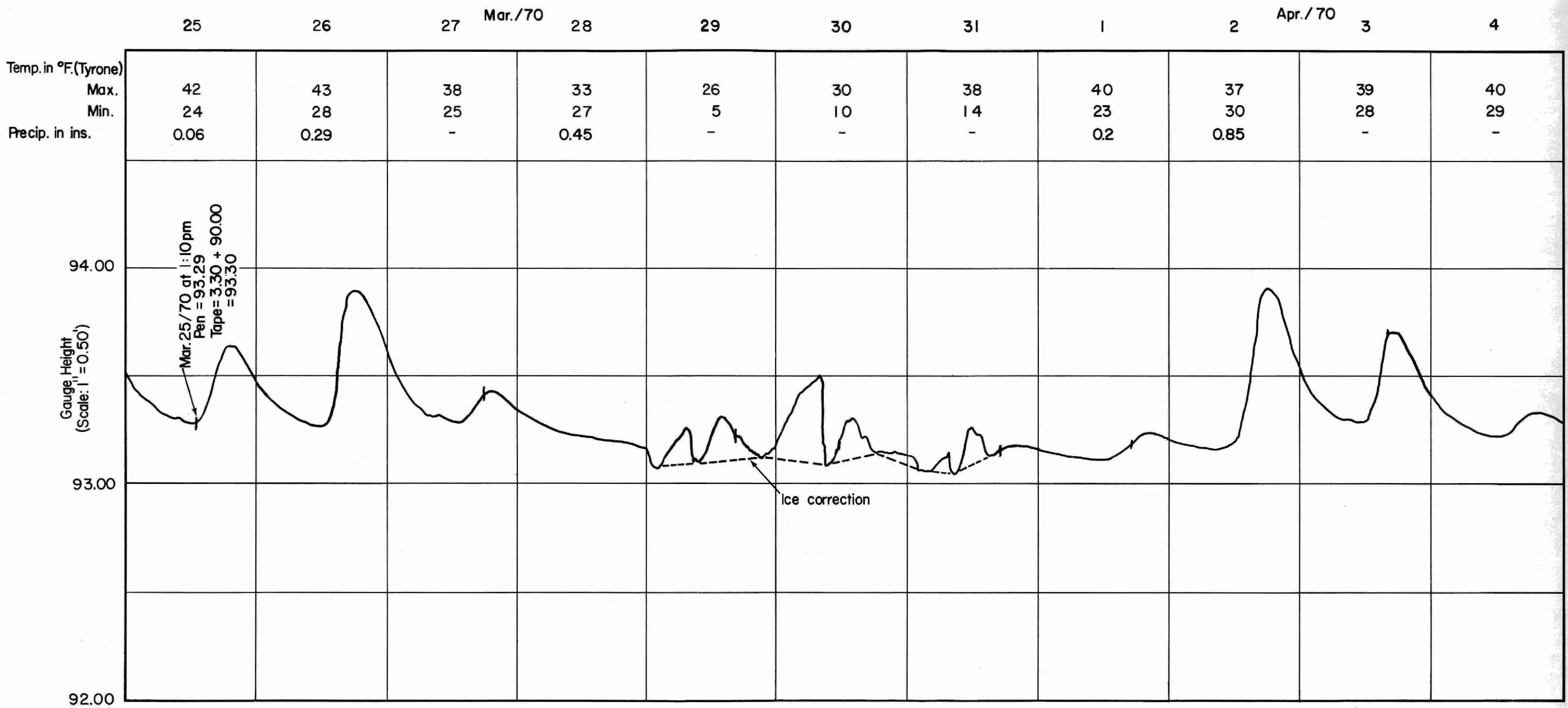


Figure I. Stream-stage hydrograph for station S-2, Mar. 25/70 to Apr. 4/70.

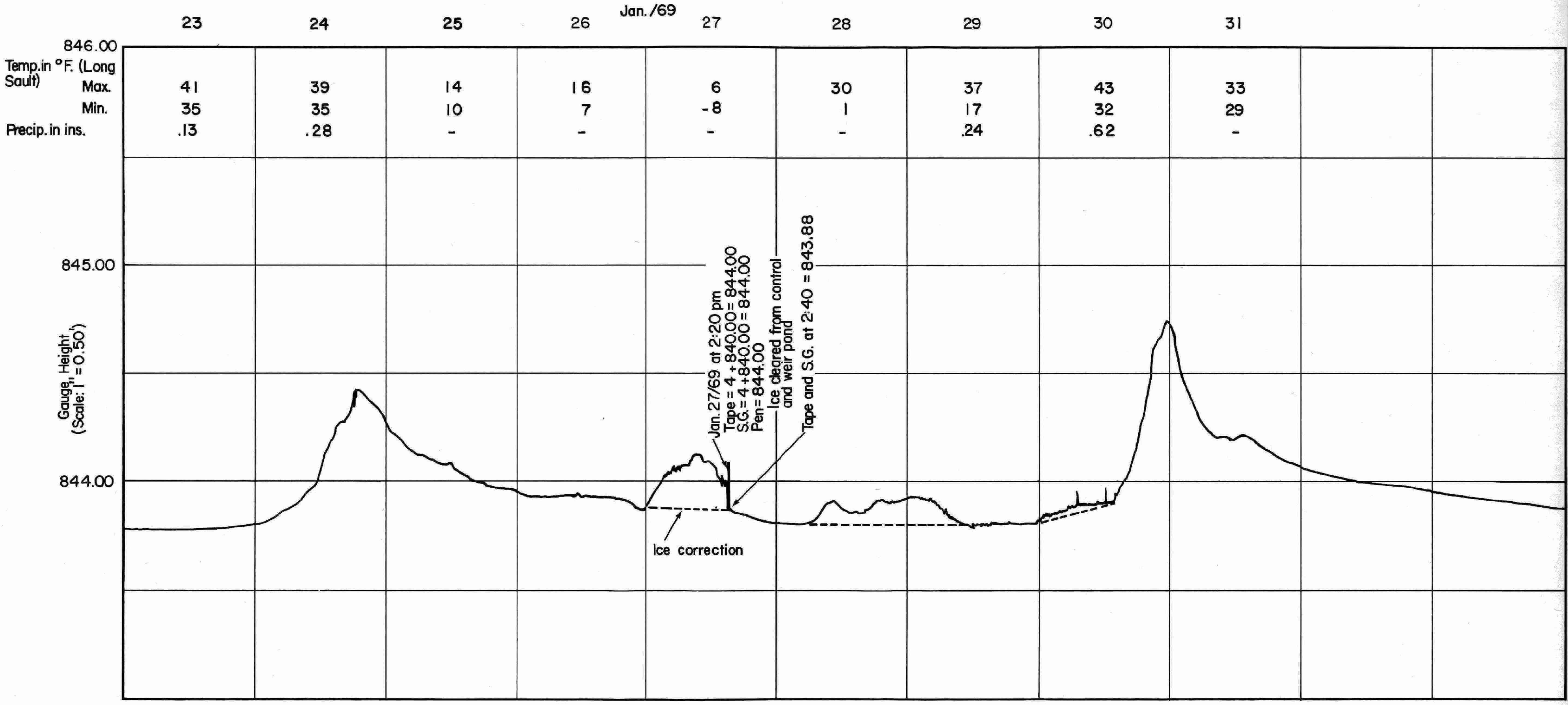


Figure 2. Stream-stage hydrograph for station B-1, Jan. 23/69 to Jan. 31/69.

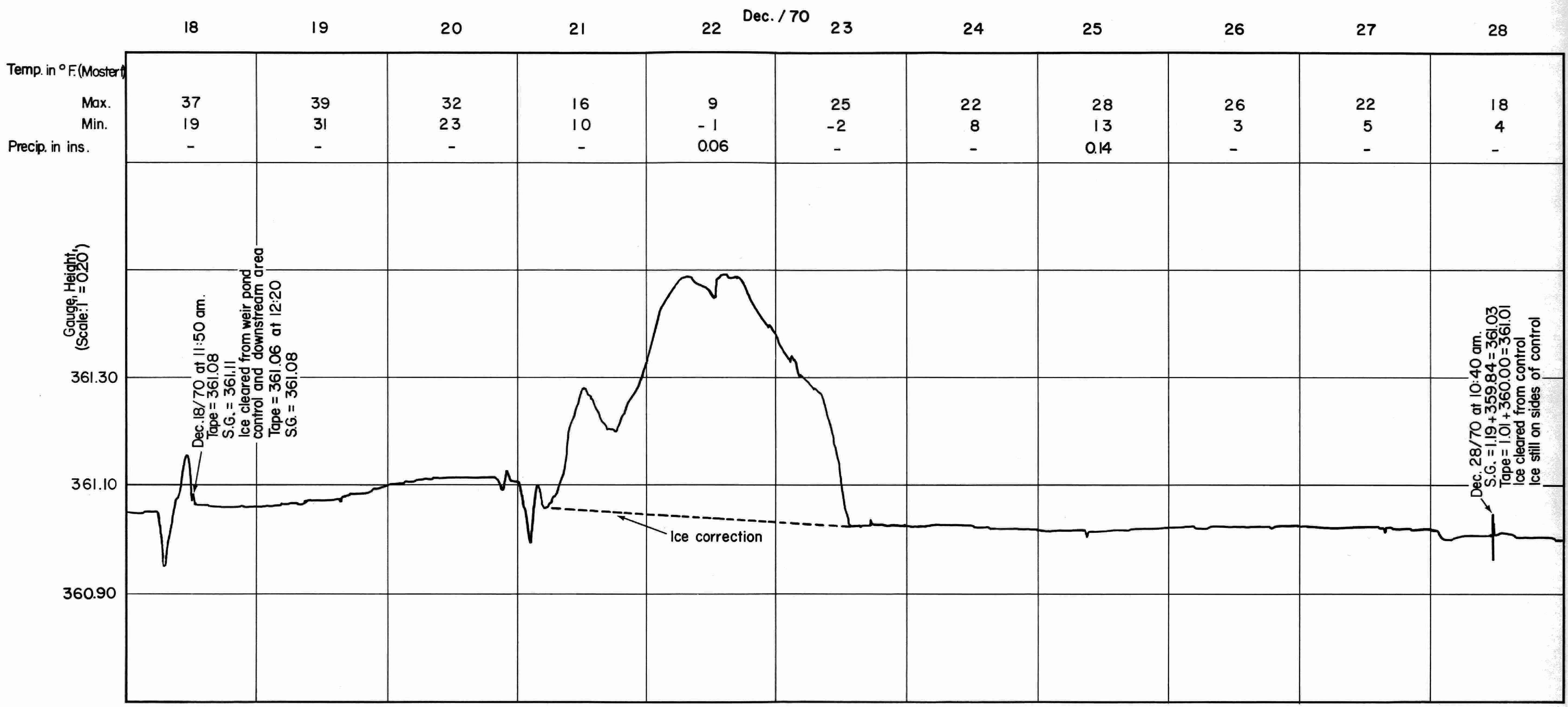


Figure 3. Stream-stage hydrograph for station W-3, Dec. 18/70 - Dec. 28/70.

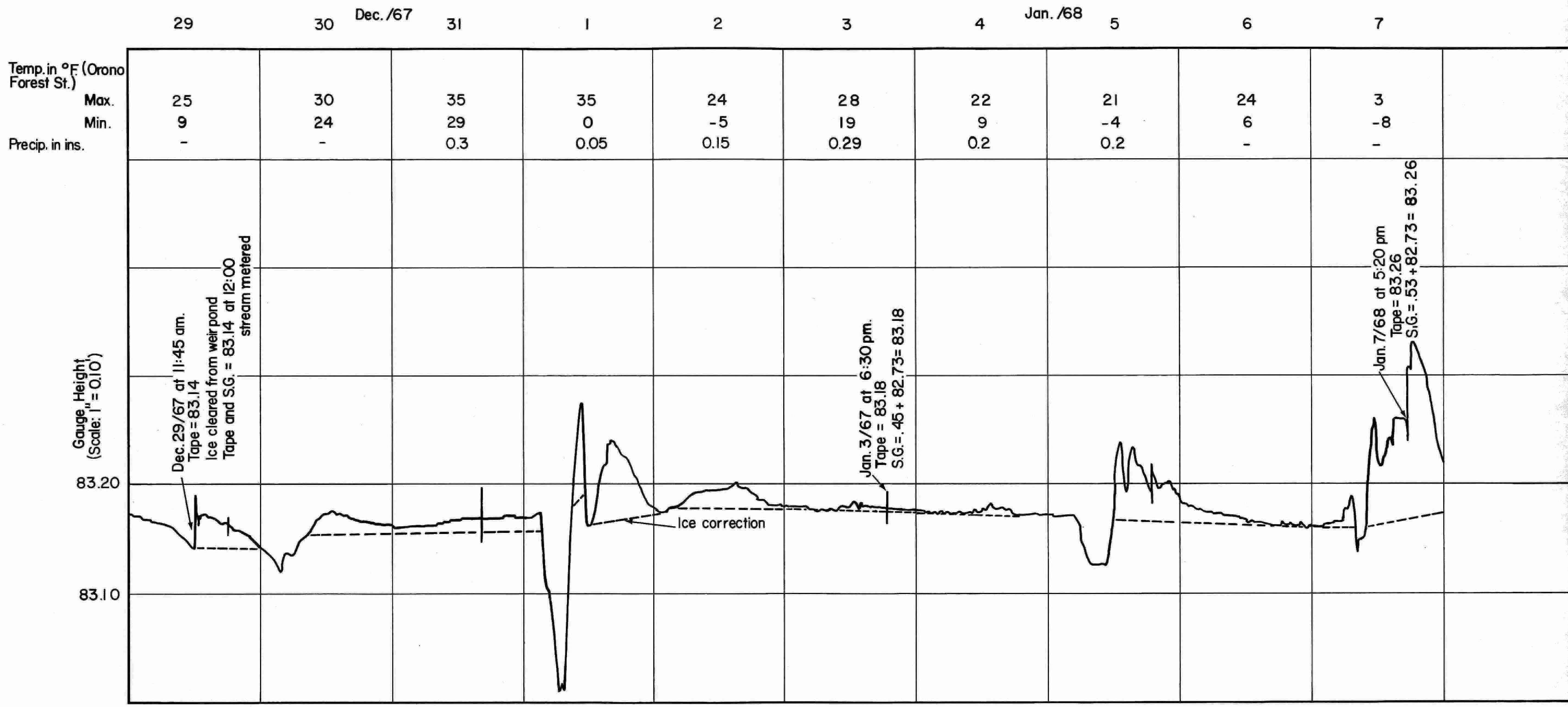


Figure 4a. Stream-stage hydrograph for station S-3, Dec. 28/67 - Jan. 7/68.

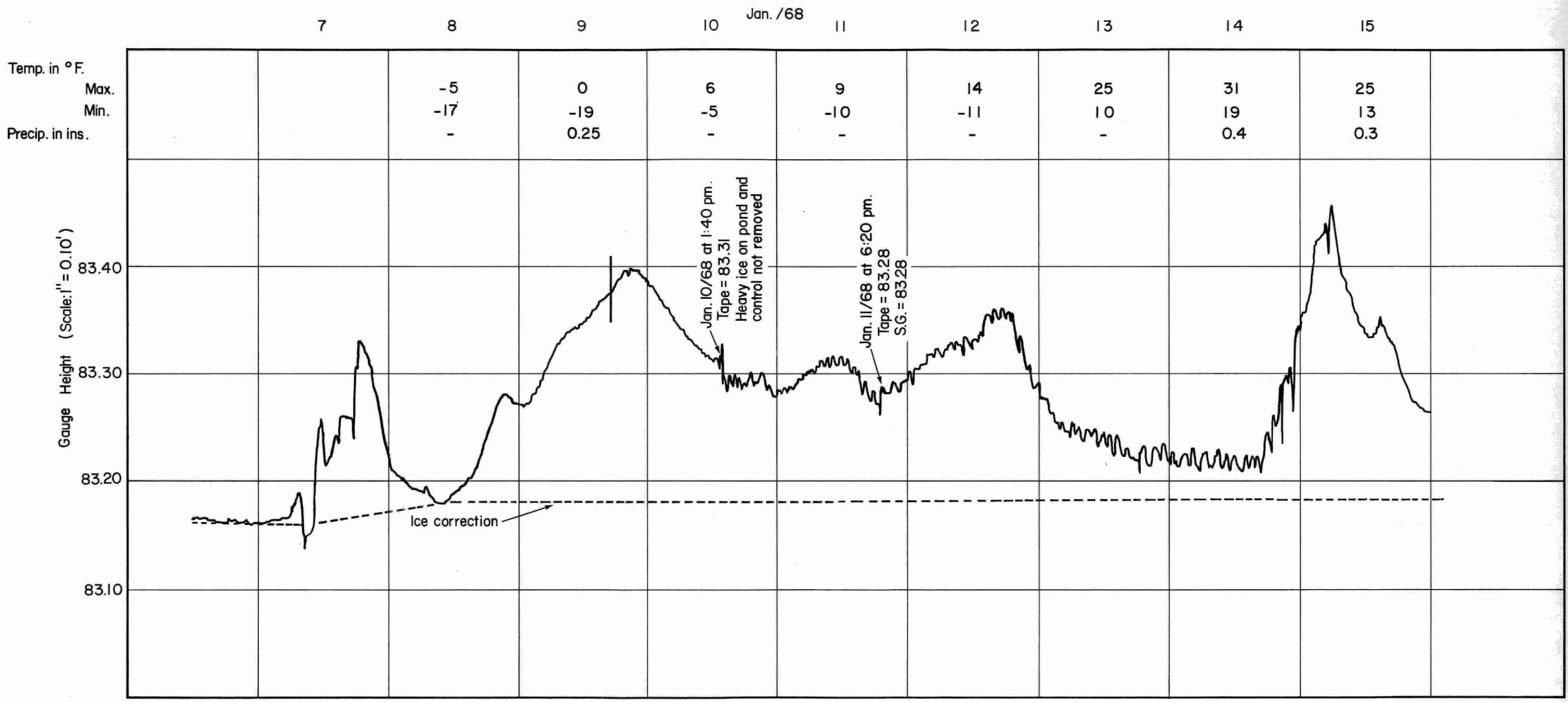


Figure 4b. Stream-stage hydrograph for station S-3, Jan.7/68 - Jan.15/68.

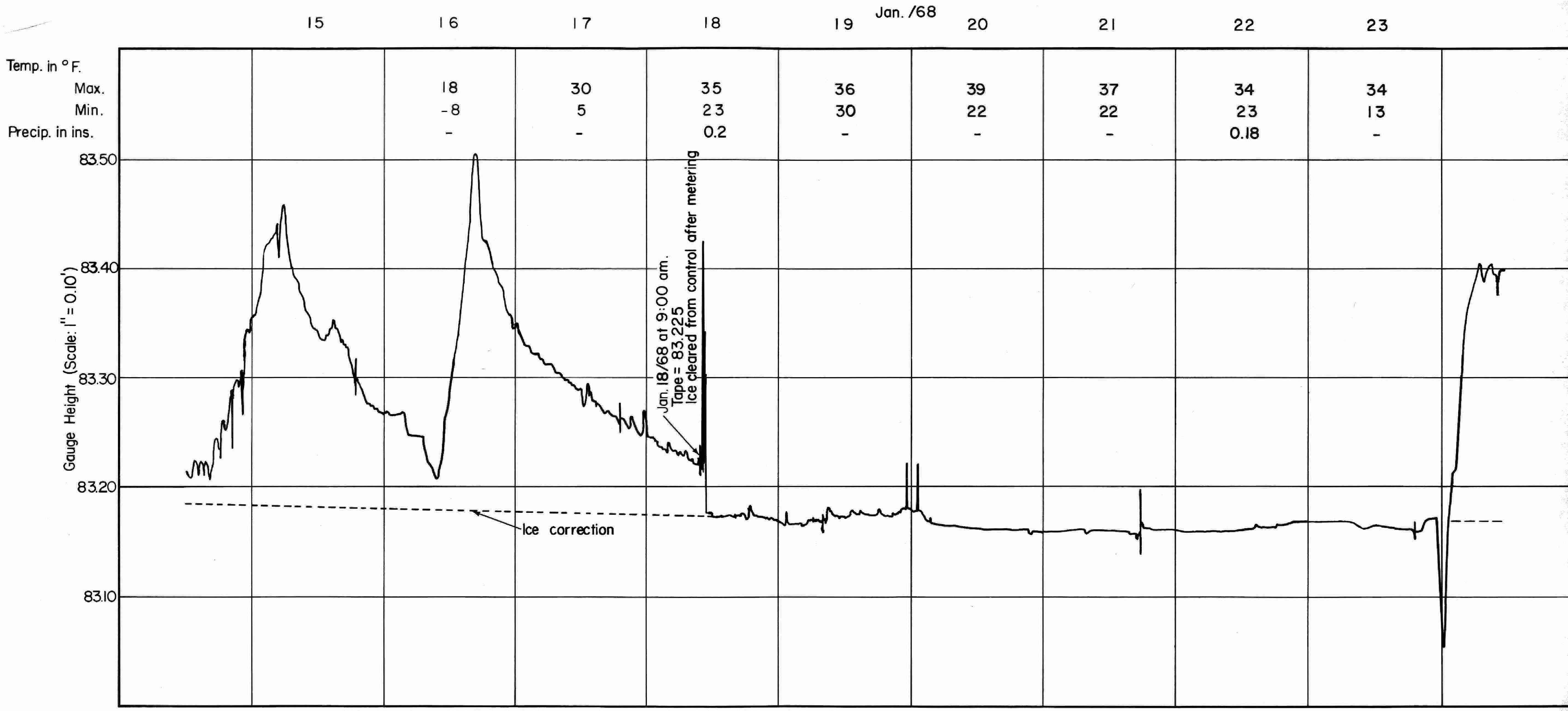


Figure 4c. Stream-stage hydrograph for station S-3, Jan. 15/68 - Jan. 23/68.

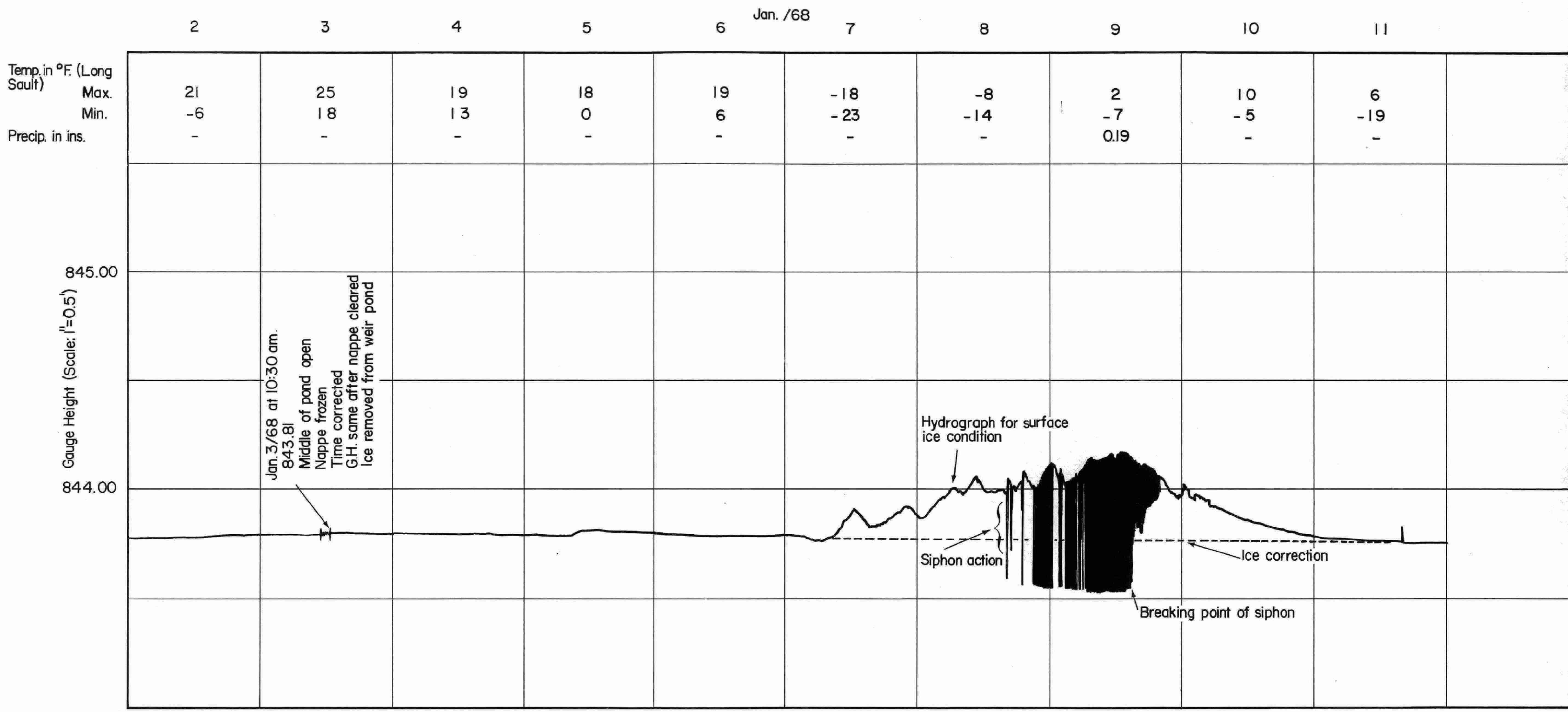


Figure 5. Stream-stage hydrograph for station B-1, Jan.2/68 - Jan.11/68.

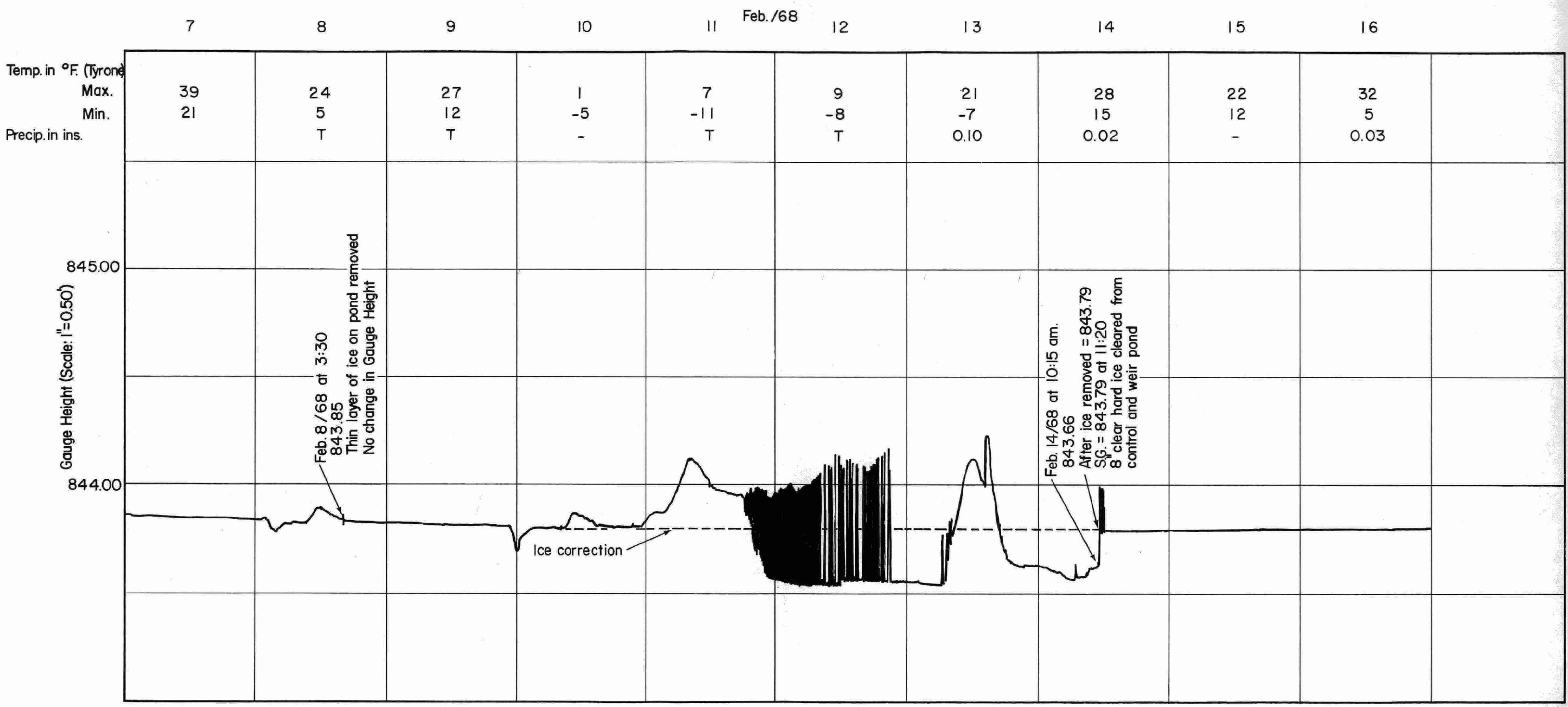


Figure 6. Stream - stage hydrograph for station B-1, Feb. 7/68 - Feb. 16/68.

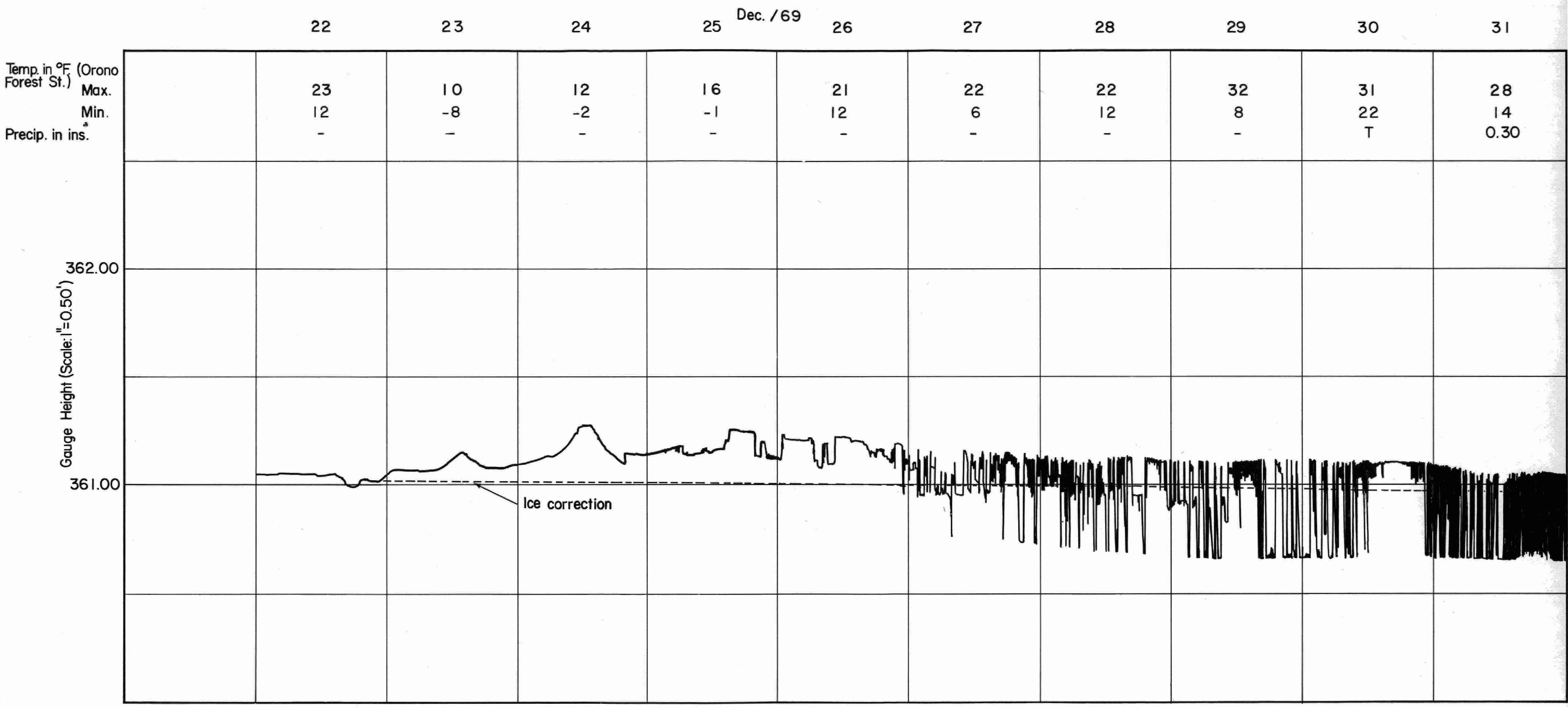


Figure 7a. Stream-stage hydrograph for station W-3, Dec. 22/69 - Dec. 31/69.

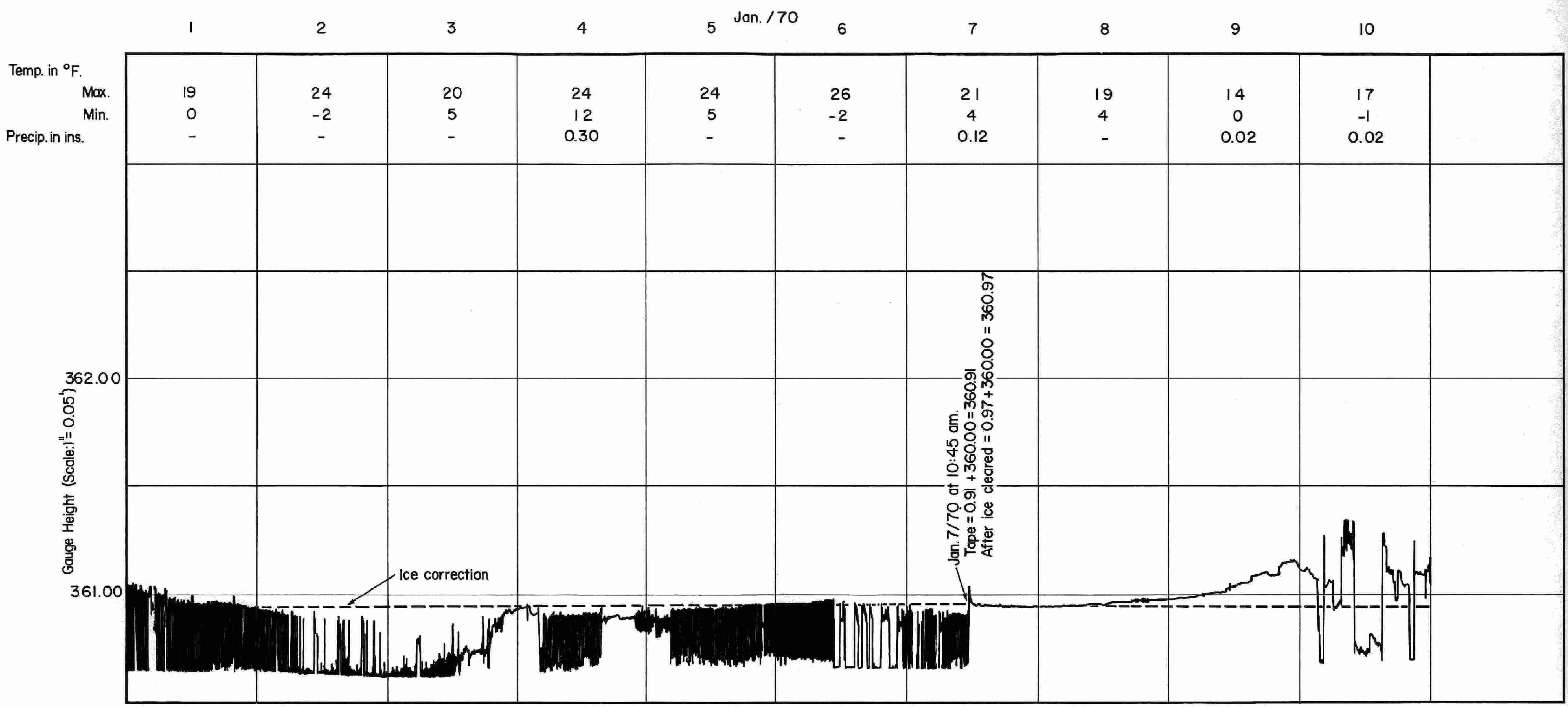


Figure 7b. Stream-stage hydrograph for station W-3, Jan. 1/70 - Jan. 10/70.

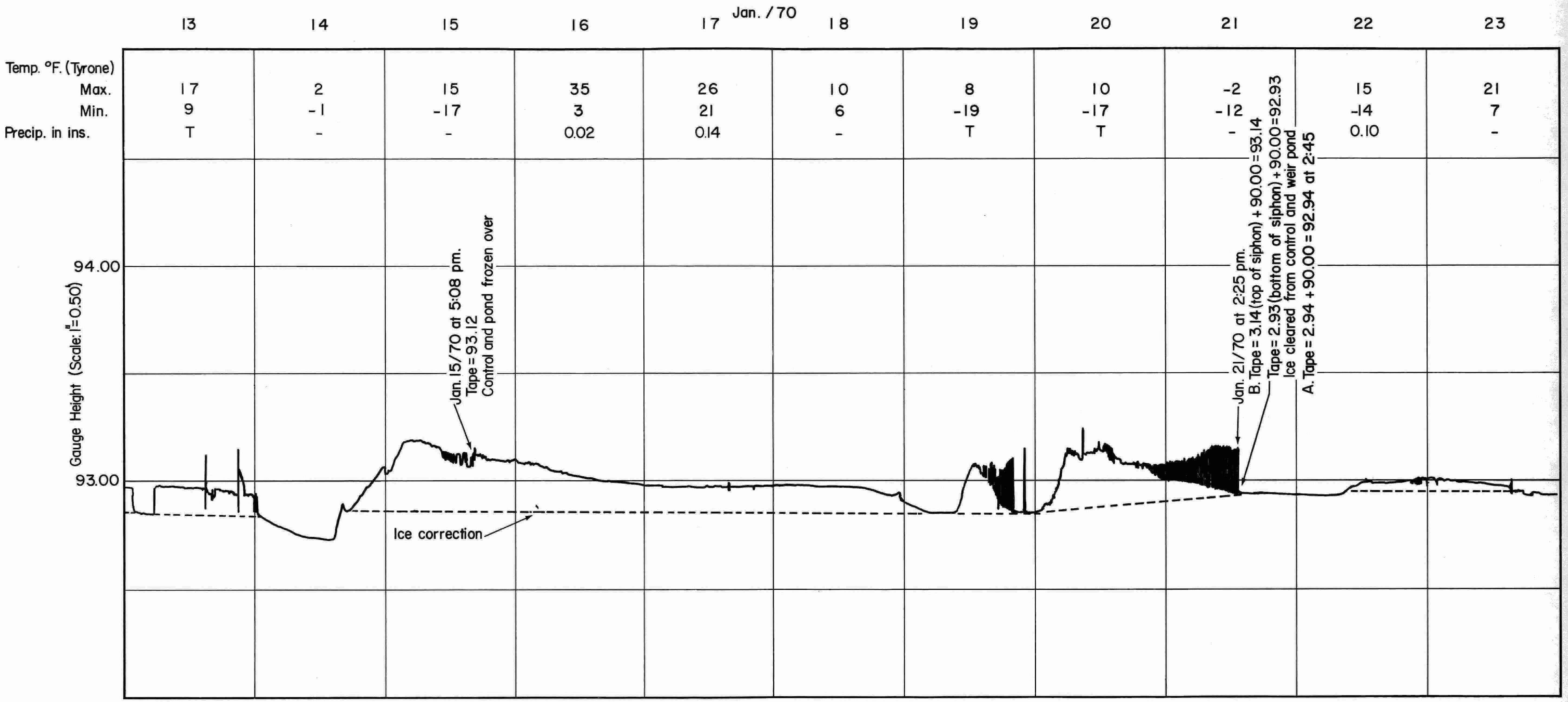


Figure 8. Stream-stage hydrograph for station S-2, Jan. 13/70 - Jan. 23/70.

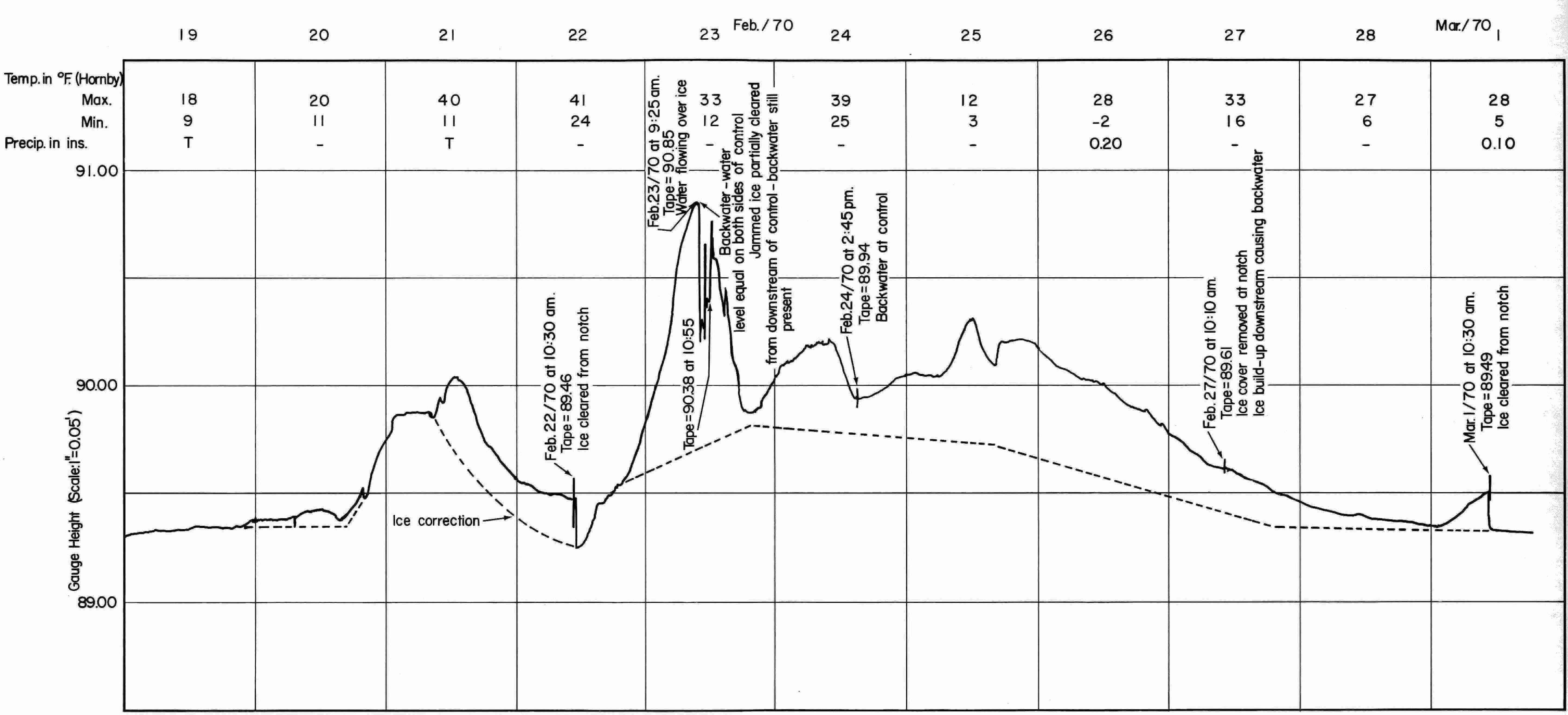


Figure 9. Stream-stage hydrograph for station O-4, Feb. 19/70 - Mar. 1/70.

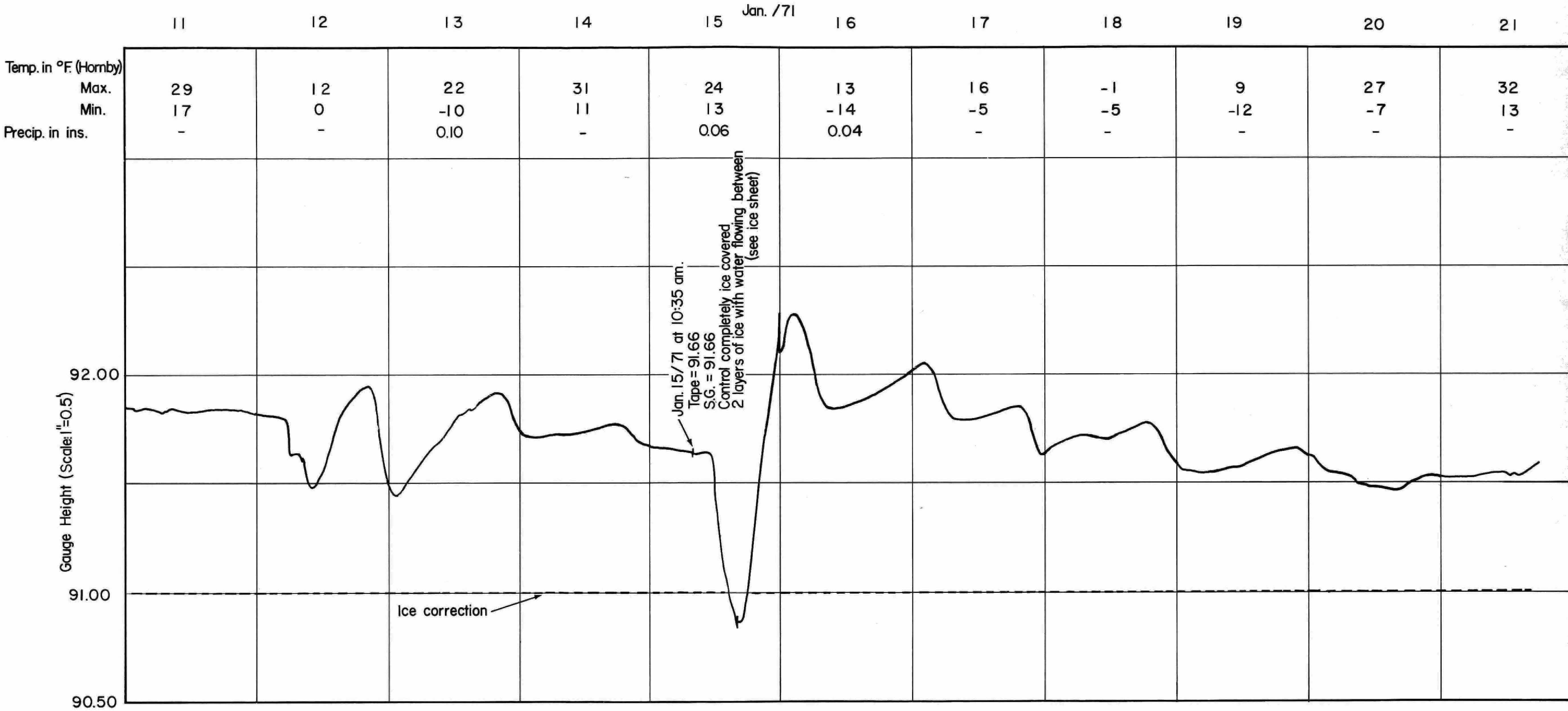


Figure 10. Stream-stage hydrograph for station O-2, Jan. 11/71 - Jan. 21/71.

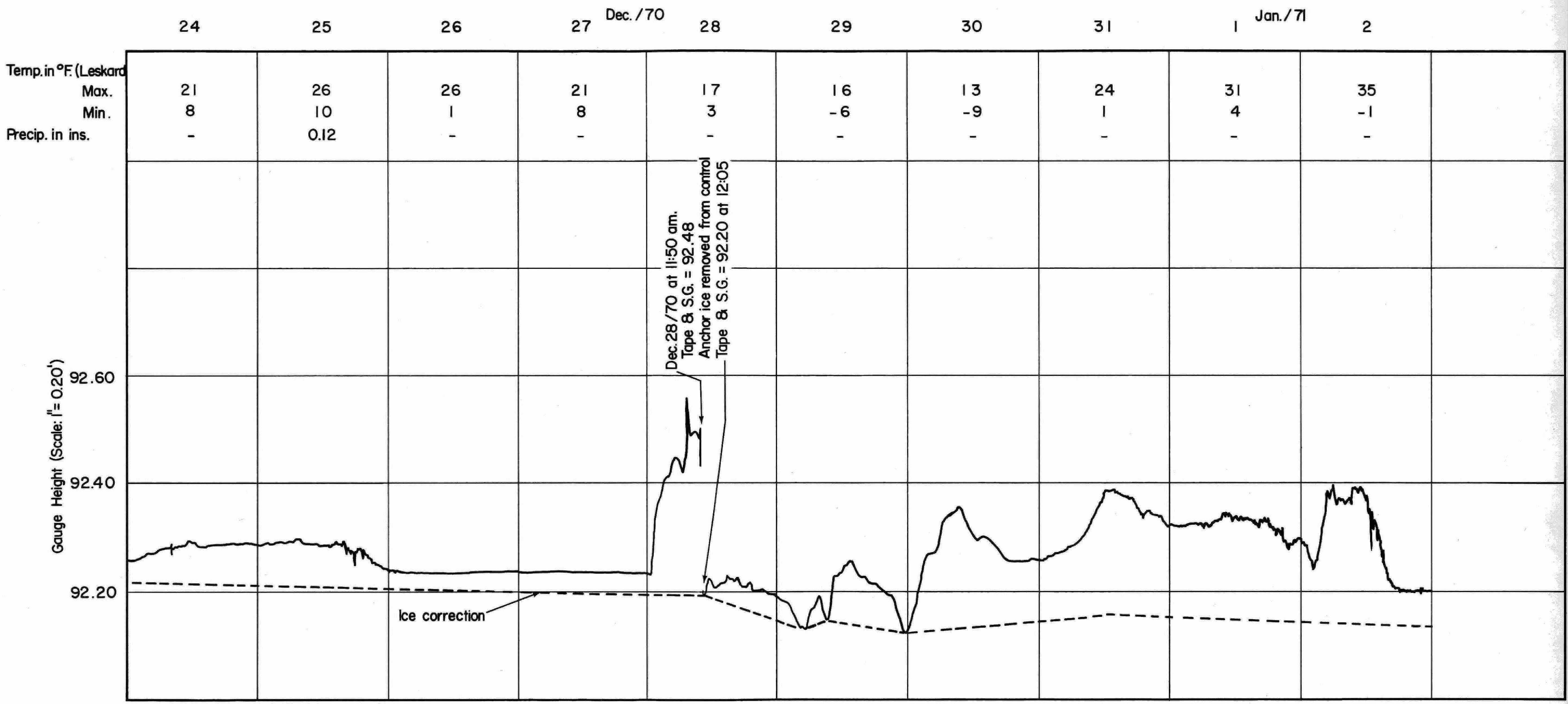
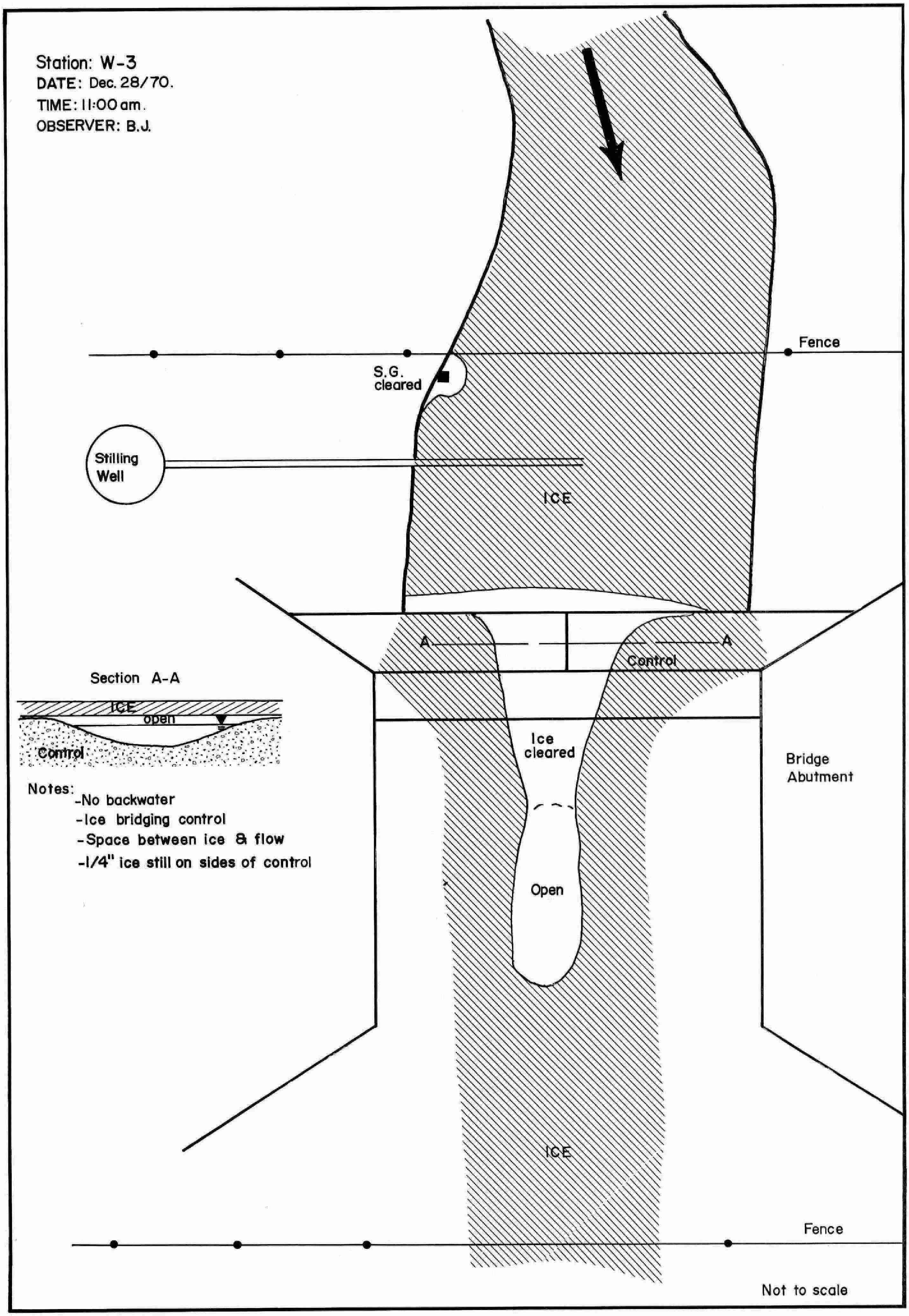


Figure 11. Stream-stage hydrograph for station W-2, Dec. 24/70 - Jan. 2/71.

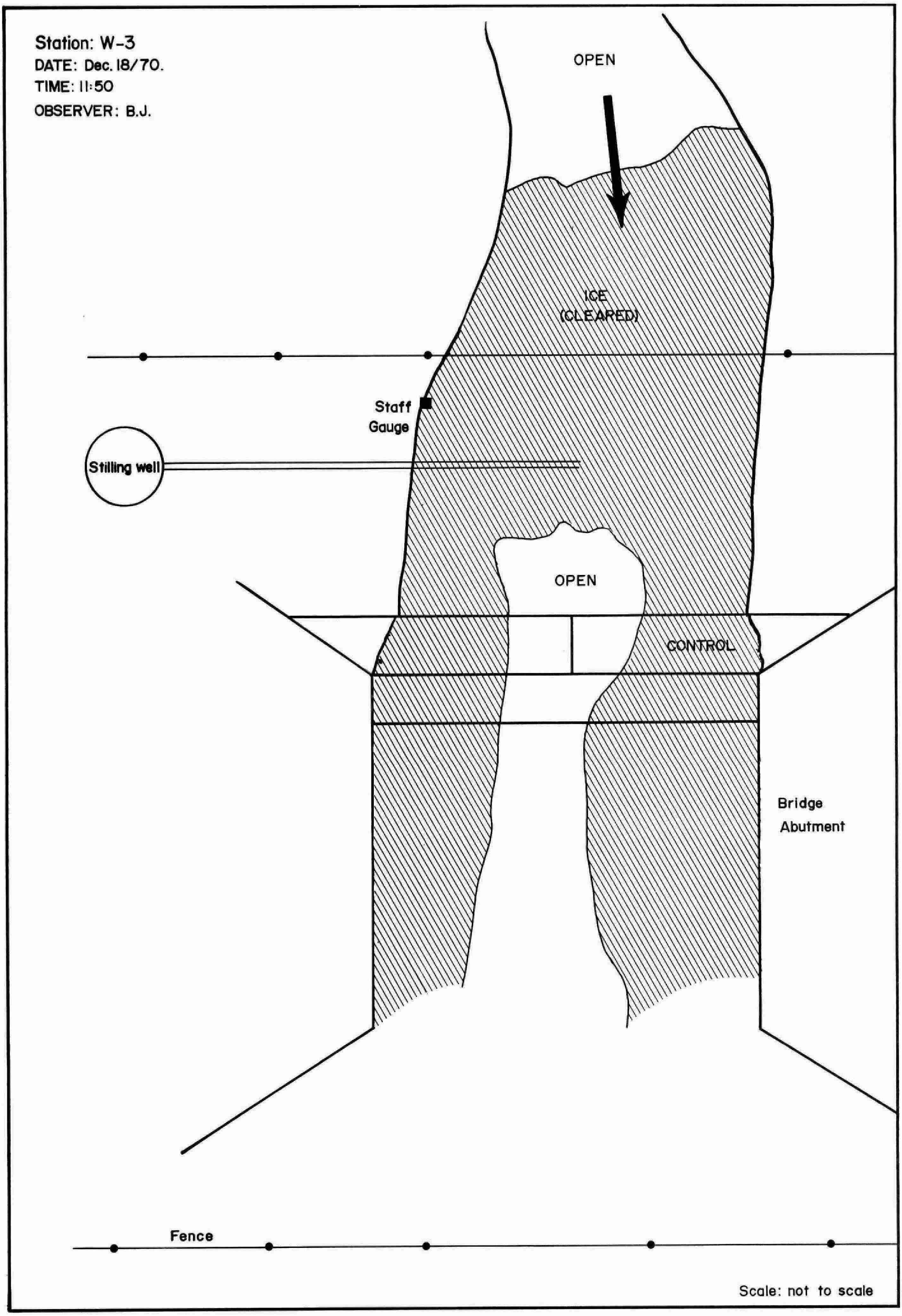
APPENDIX C

ICE SHEETS



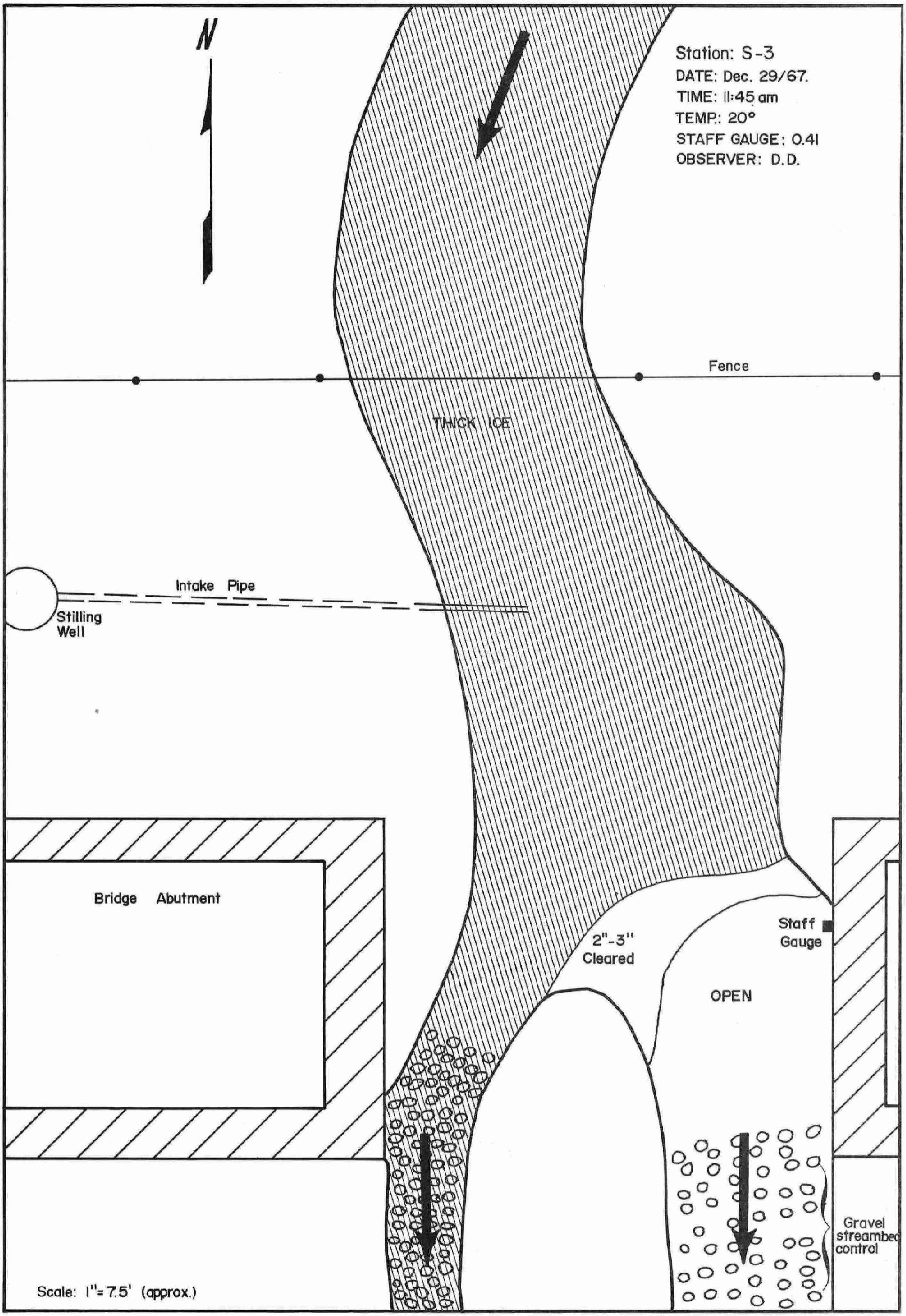
Station: W-3
DATE: Dec. 28/70.
TIME: 11:00 am.
OBSERVER: B.J.
Fence
S.G. cleared
Stilling Well
ICE
A
A
Control
Section A-A
ICE
open
Control
Notes:
-No backwater
-Ice bridging control
-Space between ice & flow
-1/4" ice still on sides of control
Ice cleared
Open
Bridge Abutment
ICE
Fence
Not to scale

Ice sheet 1

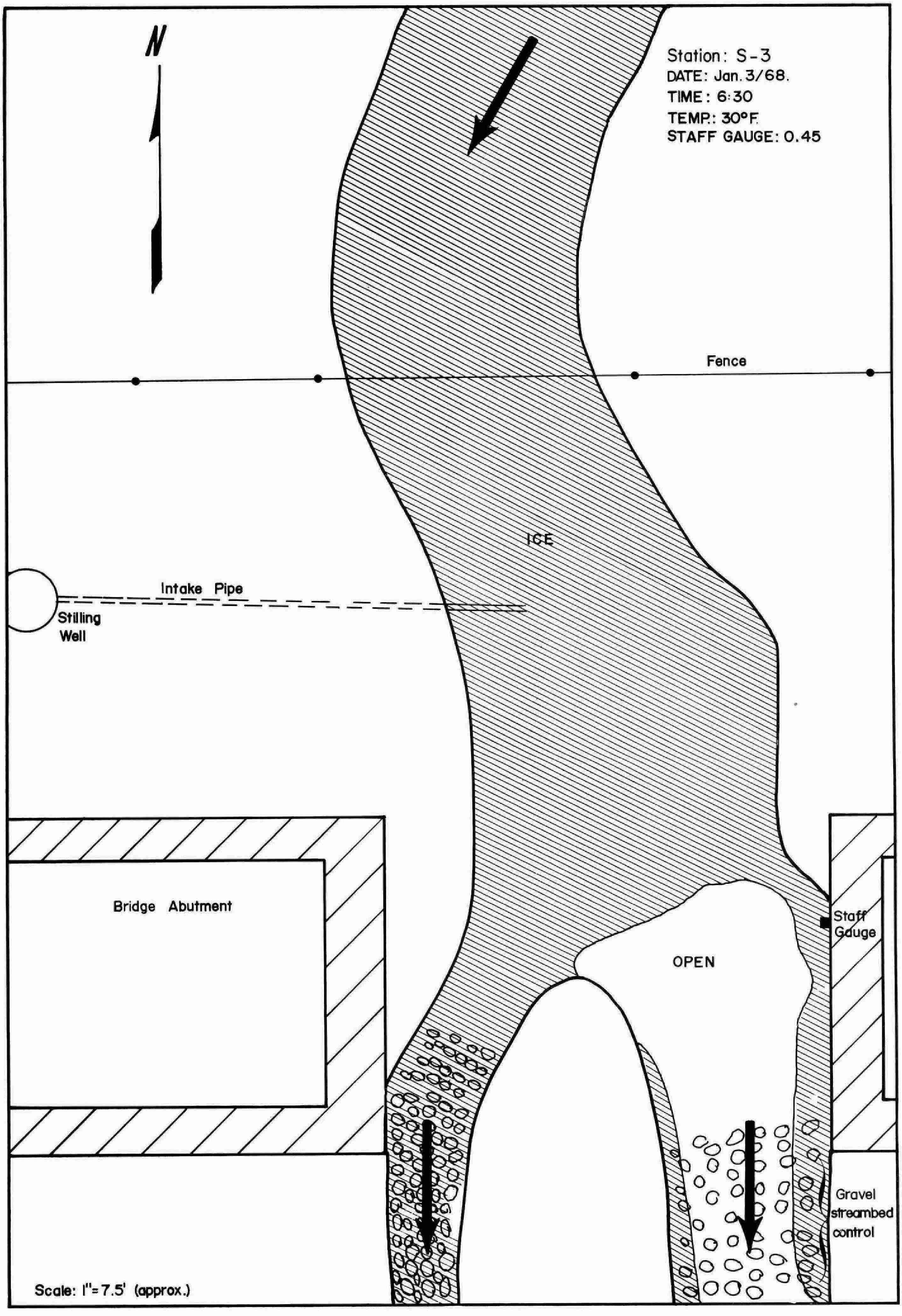


Station: W-3
DATE: Dec. 18/70.
TIME: 11:50
OBSERVER: B.J.
OPEN
ICE
(CLEARED)
Staff
Gauge
Stilling well
OPEN
CONTROL
Bridge
Abutment
Fence
Scale: not to scale

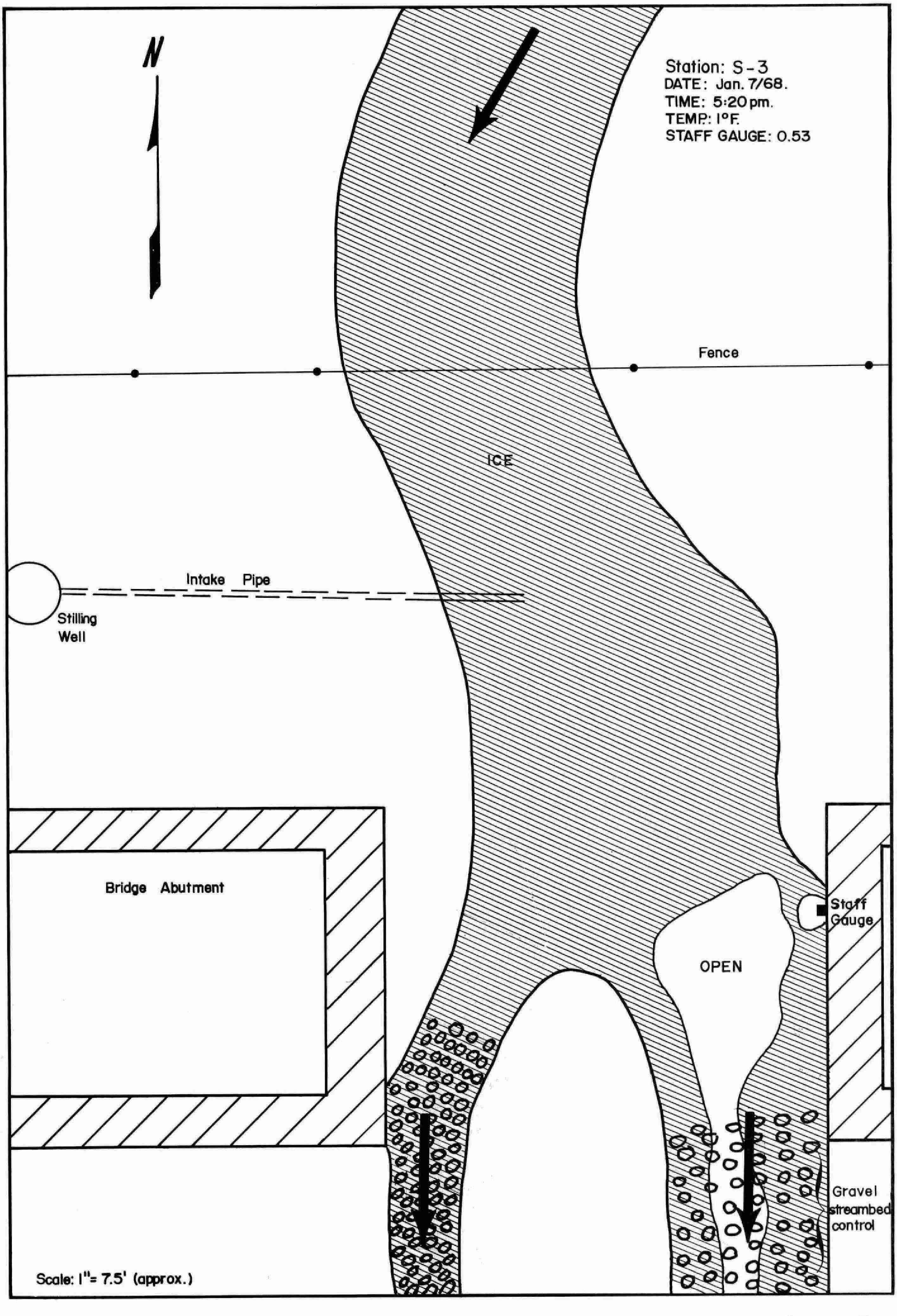
Ice sheet 2

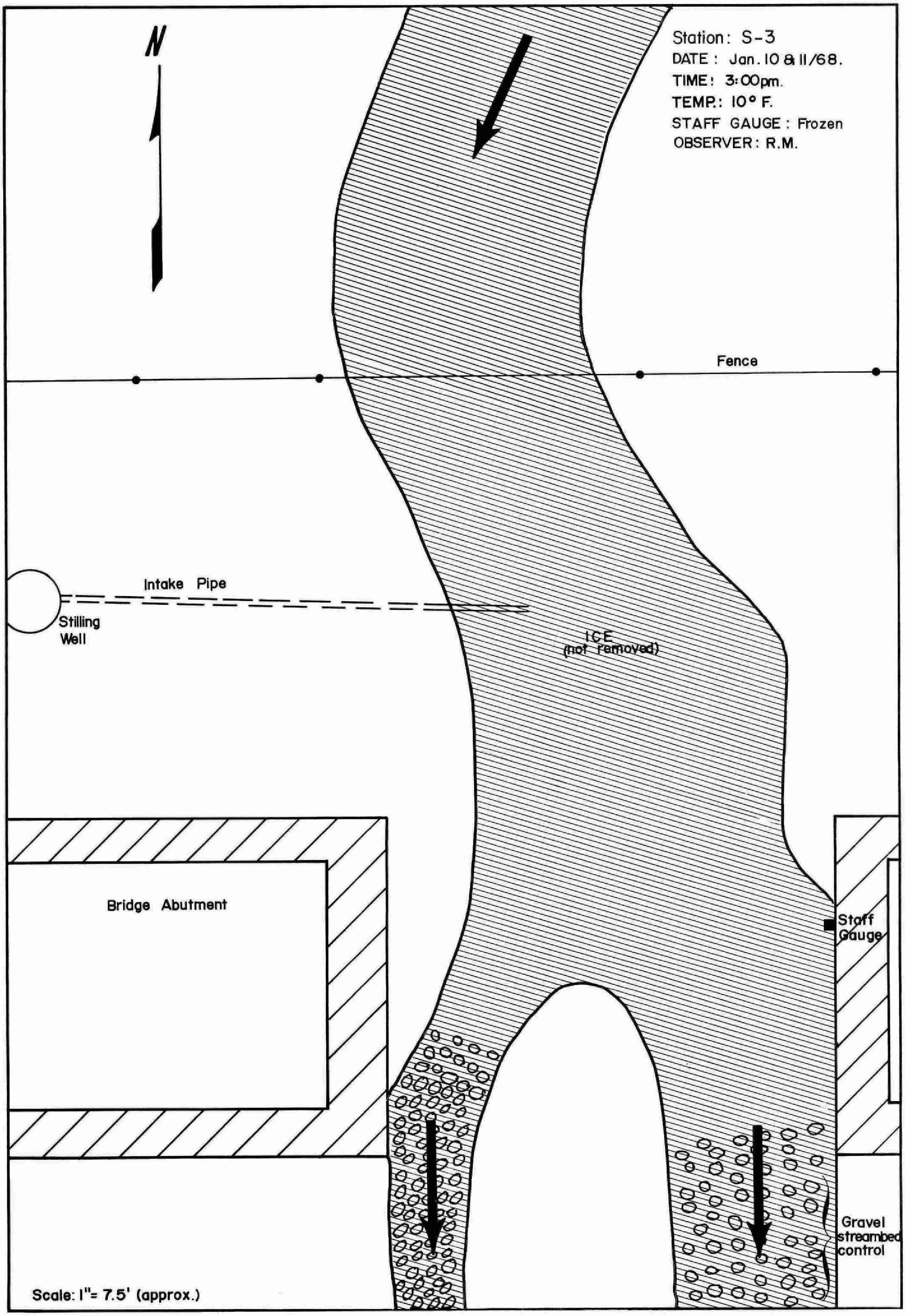

N
Station: S-3
DATE: Dec. 29/67.
TIME: 11:45 am
TEMP.: 20°
STAFF GAUGE: 0.41
OBSERVER: D.D.
Fence
THICK ICE
Intake Pipe
Stilling Well
Bridge Abutment
2"-3" Cleared
Staff Gauge
OPEN
Gravel streambed control
Scale: 1" = 7.5' (approx.)

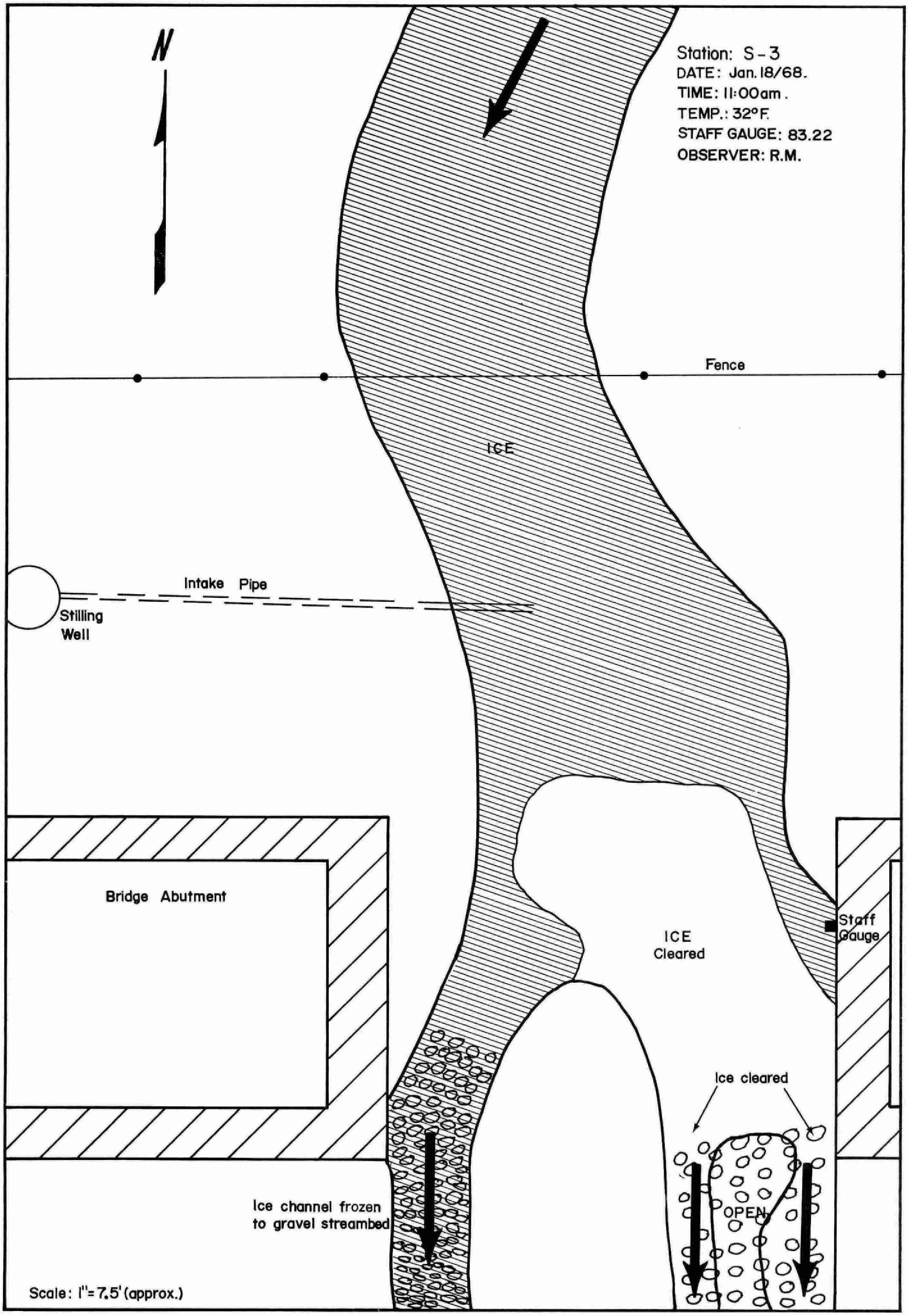
Ice sheet 3

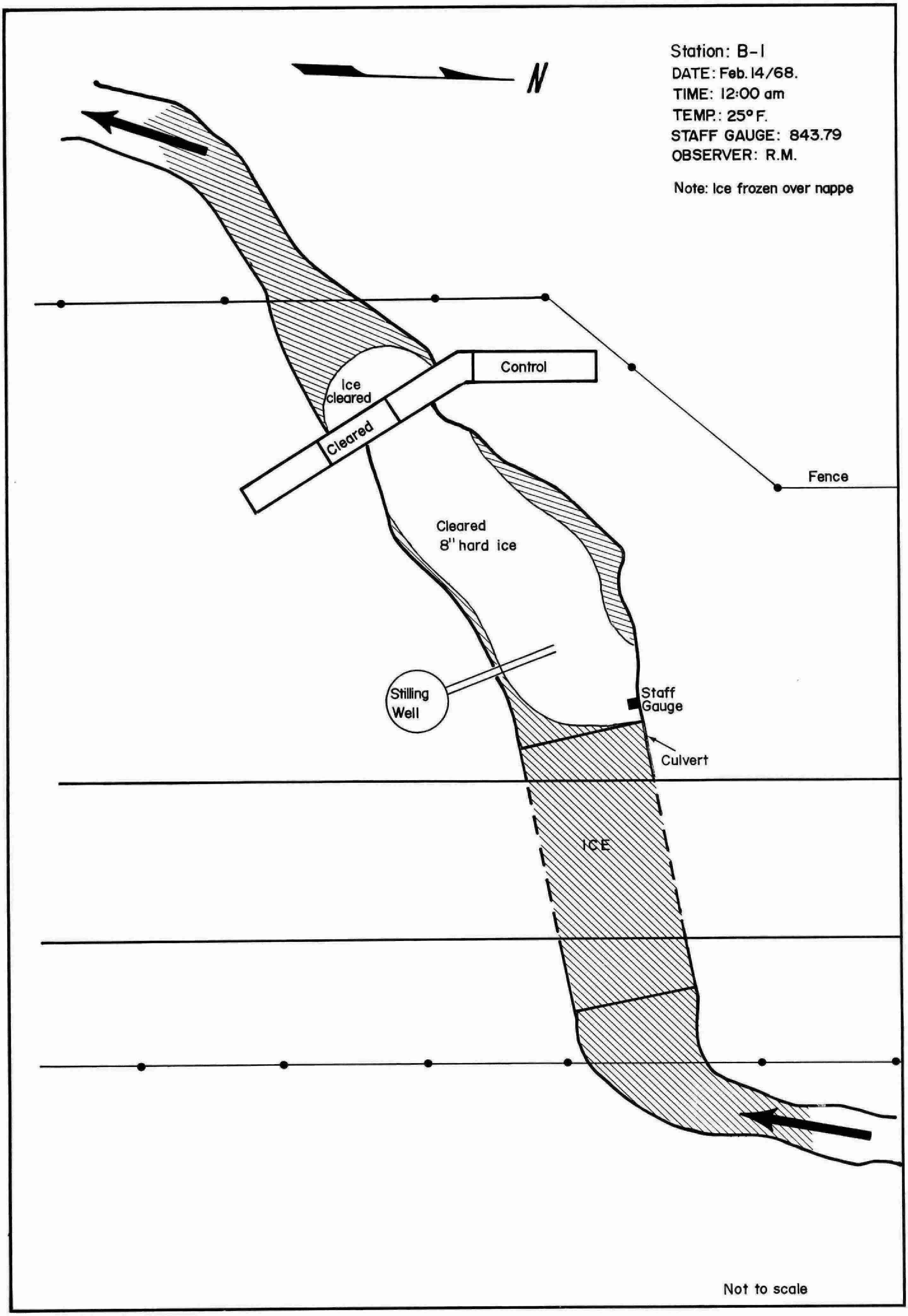

N
Station: S-3
DATE: Jan. 3/68.
TIME: 6:30
TEMP.: 30°F.
STAFF GAUGE: 0.45
Fence
ICE
Intake Pipe
Stilling Well
Bridge Abutment
Staff Gauge
OPEN
Gravel streambed control
Scale: 1"= 7.5' (approx.)

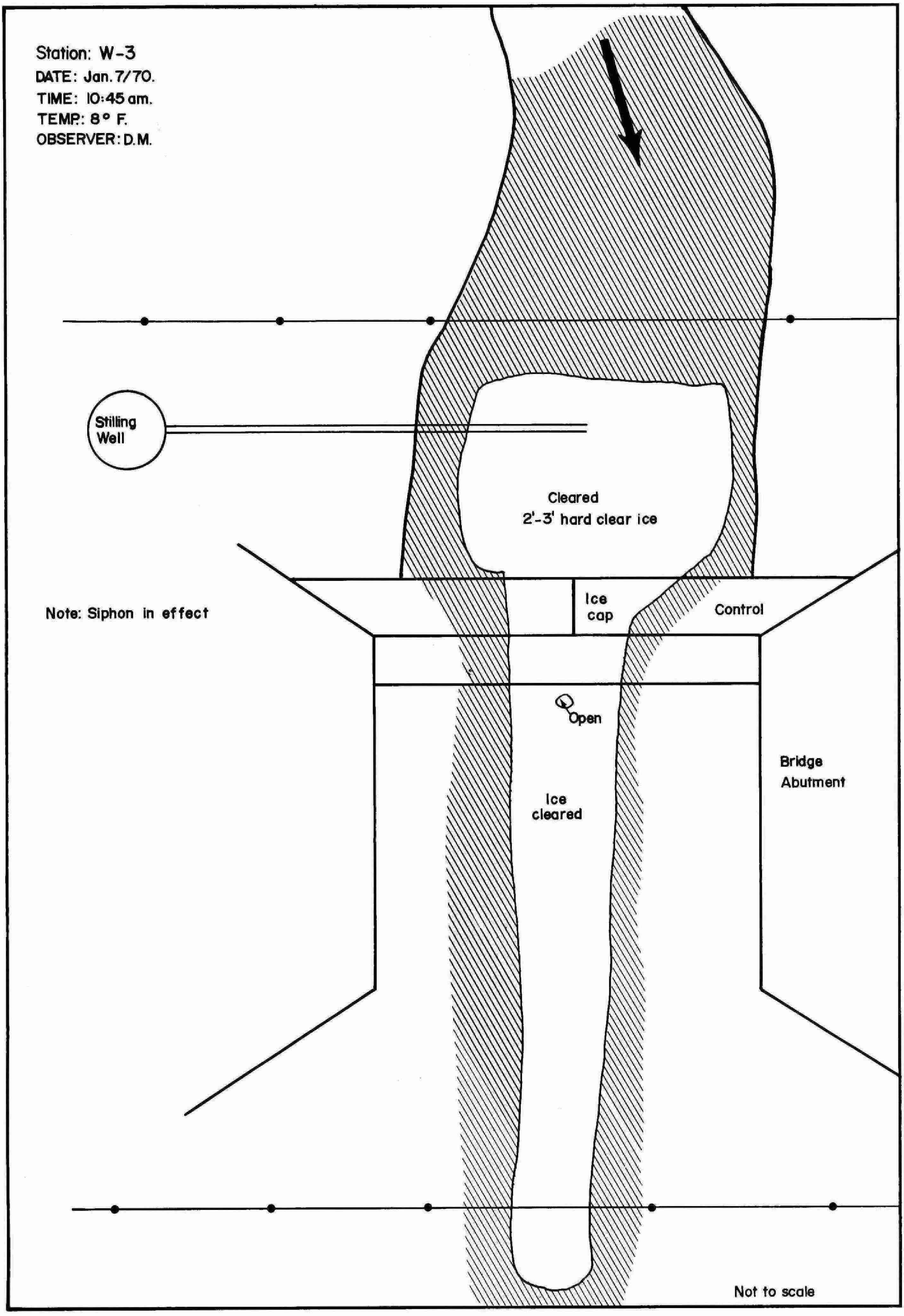
Ice sheet 4

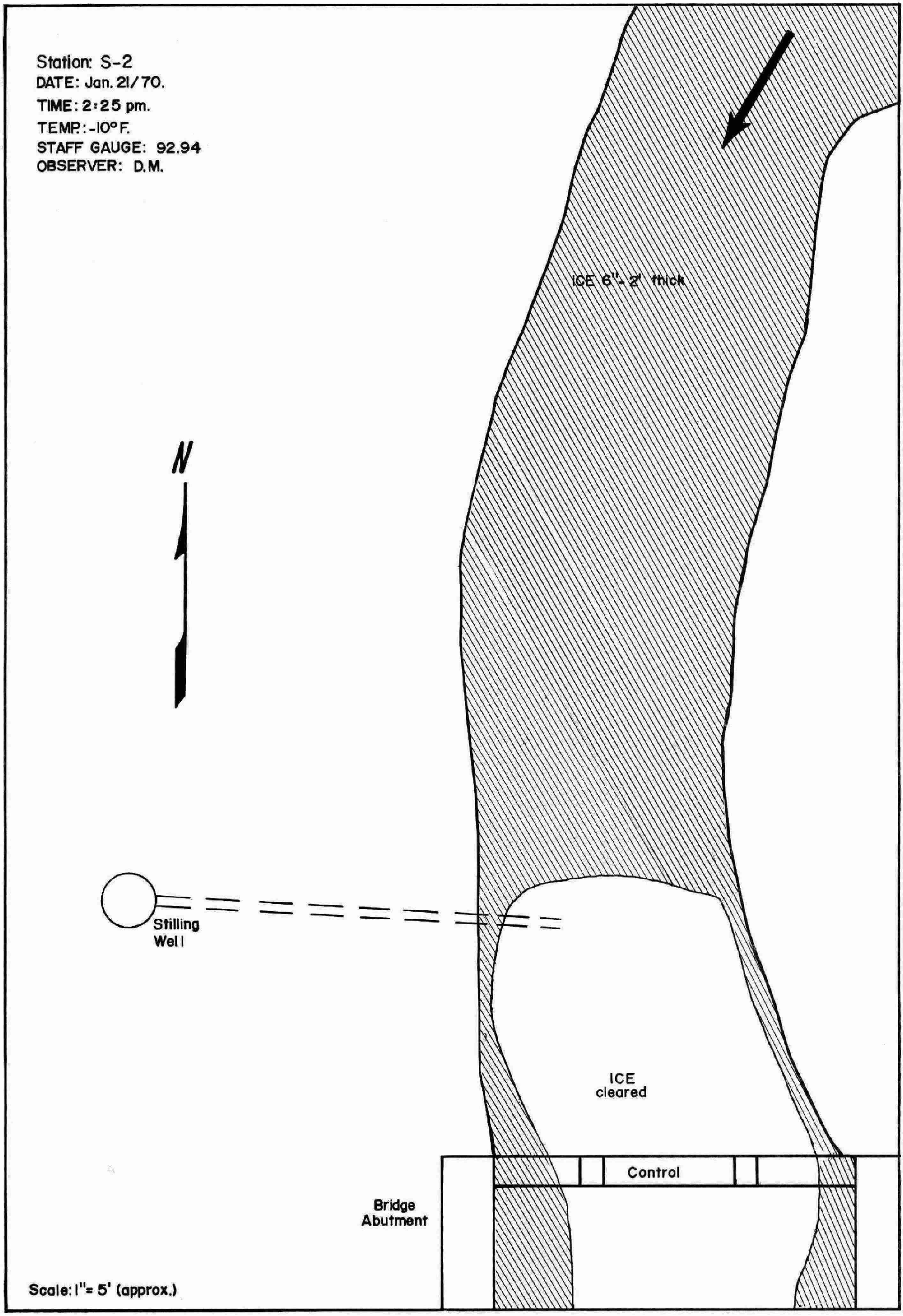

N
Station: S-3
DATE: Jan. 7/68.
TIME: 5:20 pm.
TEMP: 1°F.
STAFF GAUGE: 0.53
Fence
ICE
Intake Pipe
Stilling Well
Bridge Abutment
Staff Gauge
OPEN
Gravel streambed control
Scale: 1"= 7.5' (approx.)


N
Station: S-3
DATE: Jan. 10 & 11/68.
TIME: 3:00pm.
TEMP.: 10° F.
STAFF GAUGE: Frozen
OBSERVER: R.M.
Fence
Intake Pipe
Stilling Well
ICE (not removed)
Bridge Abutment
Staff Gauge
Gravel streambed control
Scale: 1"= 7.5' (approx.)

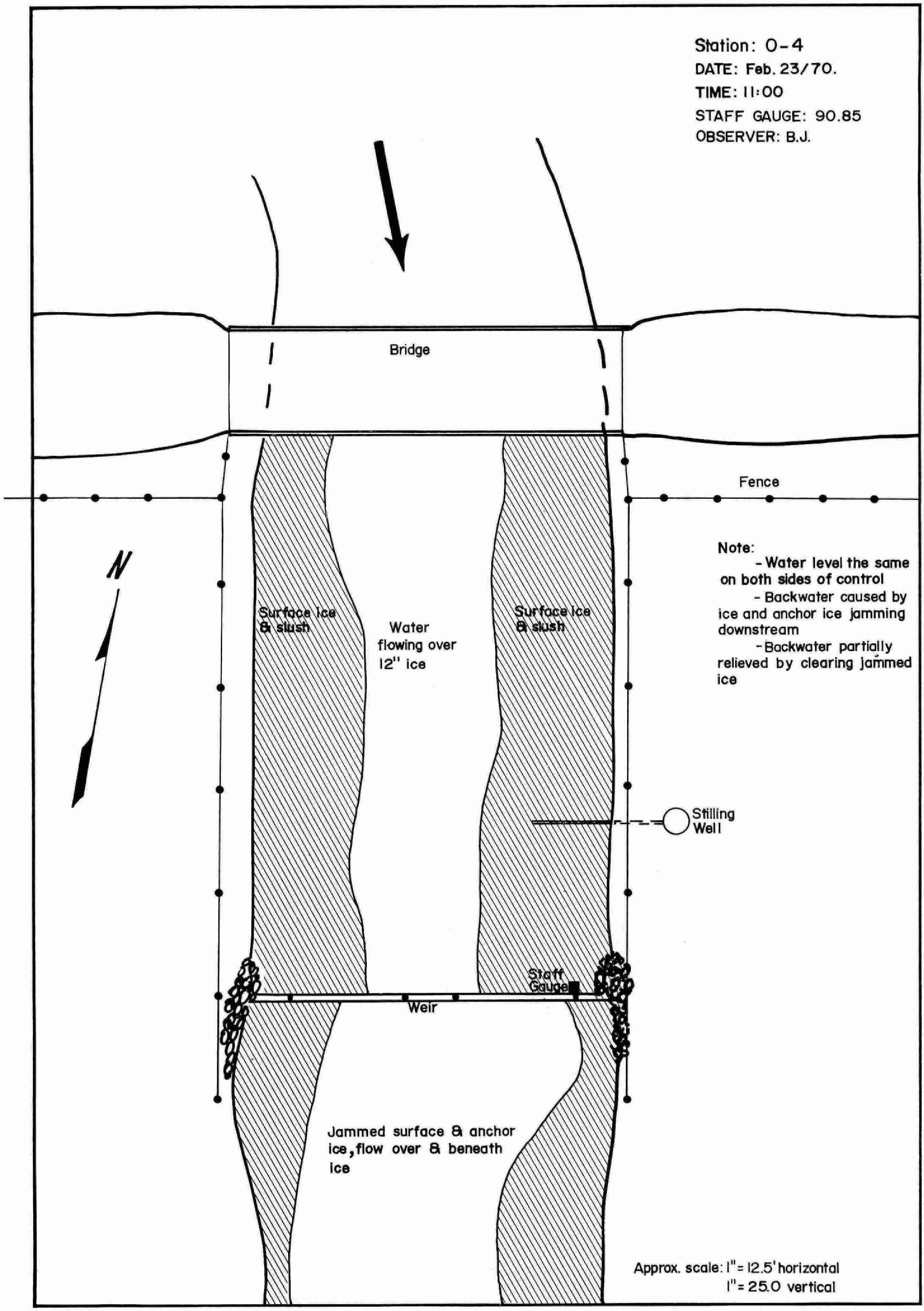

N
Station: S-3
DATE: Jan. 18/68.
TIME: 11:00am.
TEMP.: 32°F.
STAFF GAUGE: 83.22
OBSERVER: R.M.
Fence
ICE
Intake Pipe
Stilling Well
Bridge Abutment
ICE Cleared
Staff Gauge
Ice cleared
OPEN
Ice channel frozen to gravel streambed
Scale: 1"= 7.5' (approx.)


Station: B-I
DATE: Feb. 14/68.
TIME: 12:00 am
TEMP.: 25° F.
STAFF GAUGE: 843.79
OBSERVER: R.M.
Note: Ice frozen over nappe
N
Control
Ice cleared
Cleared
Fence
Cleared
8" hard ice
Stilling Well
Staff Gauge
Culvert
ICE
Not to scale

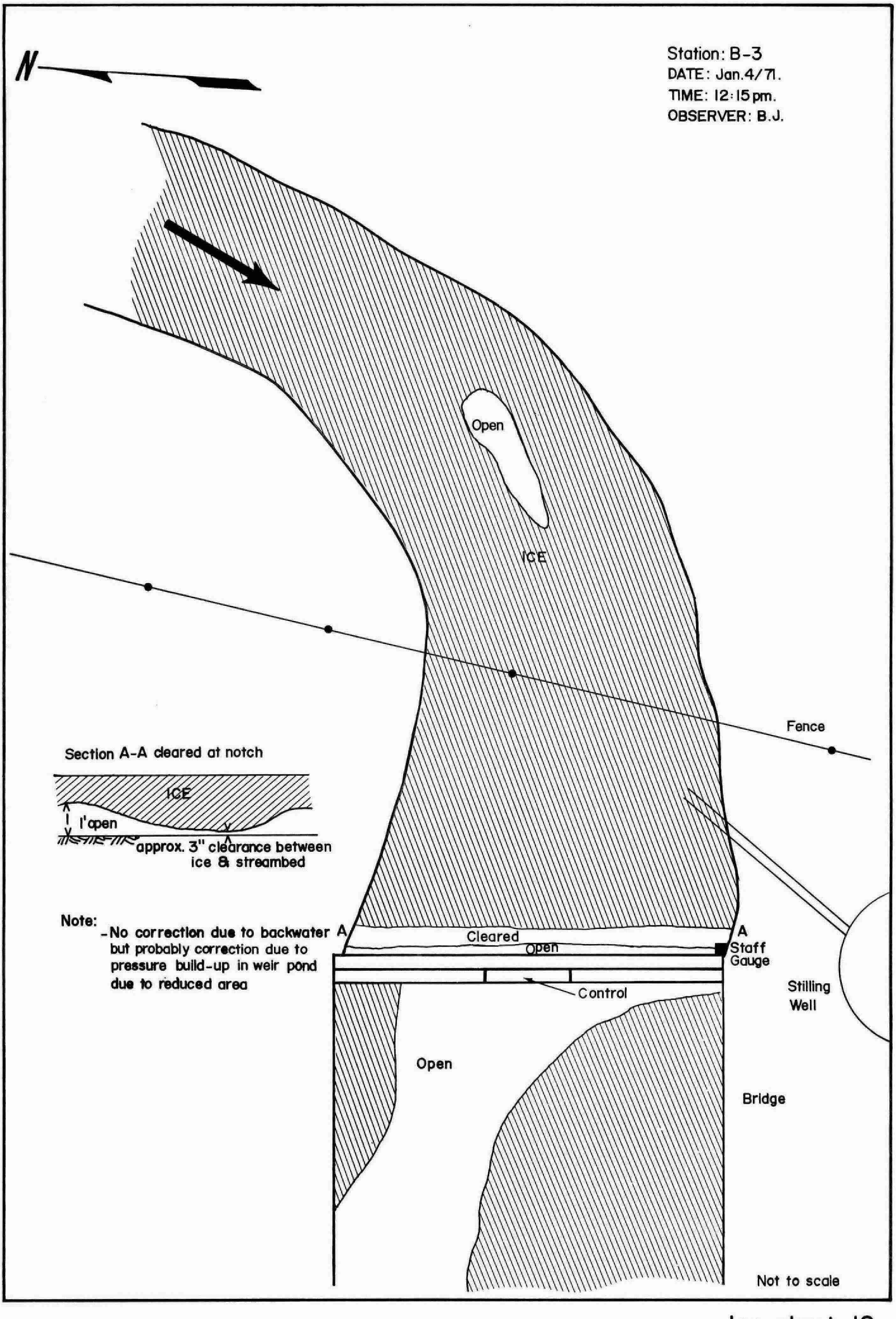

Station: W-3
DATE: Jan. 7/70.
TIME: 10:45 am.
TEMP.: 8° F.
OBSERVER: D.M.
Stilling Well
Cleared
2'-3' hard clear ice
Note: Siphon in effect
Ice cap
Control
Open
Bridge Abutment
Ice cleared
Not to scale


Station: S-2
DATE: Jan. 21/70.
TIME: 2:25 pm.
TEMP.: -10°F.
STAFF GAUGE: 92.94
OBSERVER: D.M.
ICE 6"- 2' thick
N
Stilling
Well
ICE
cleared
Control
Bridge
Abutment
Scale: 1"= 5' (approx.)

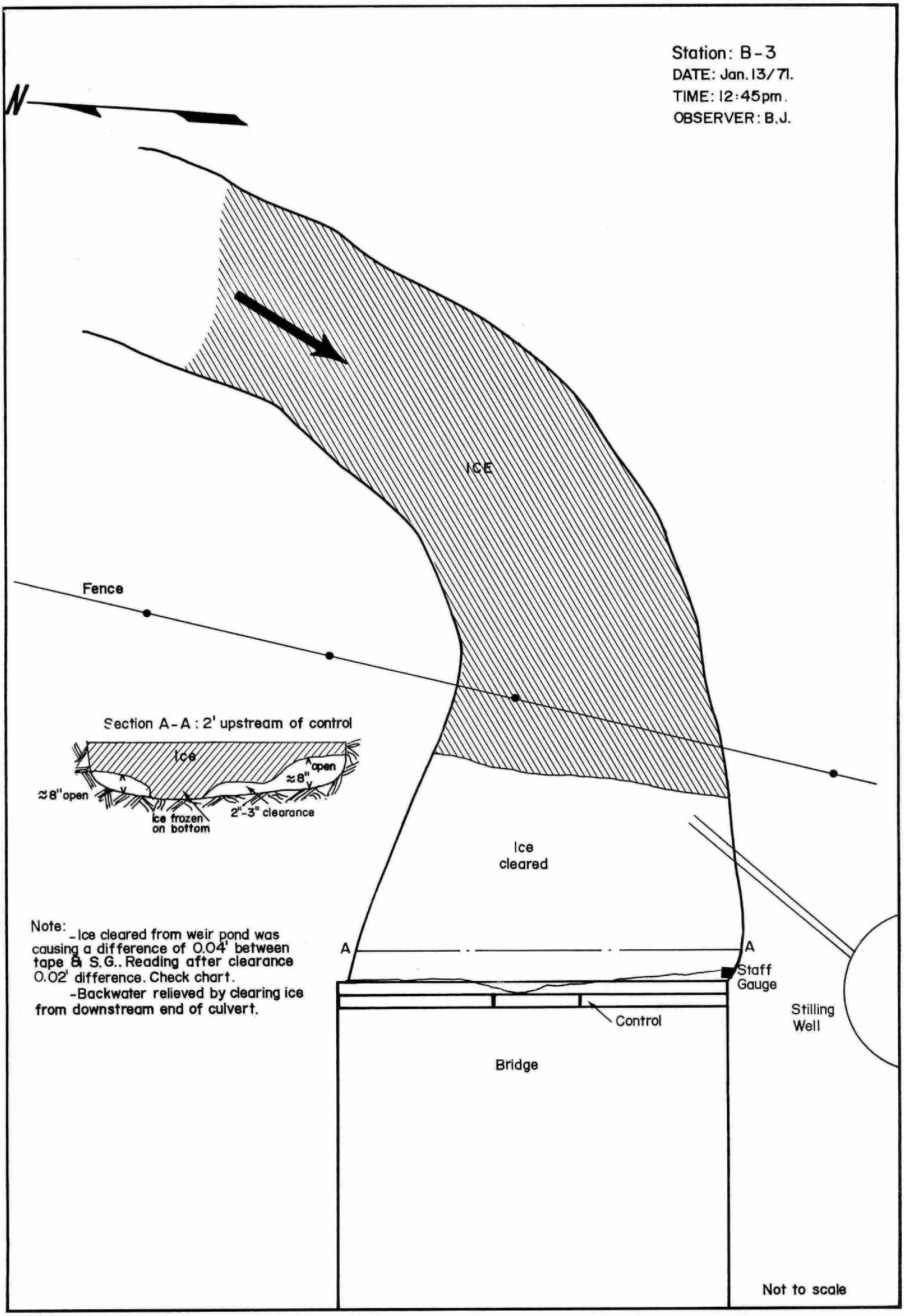
Ice sheet 10

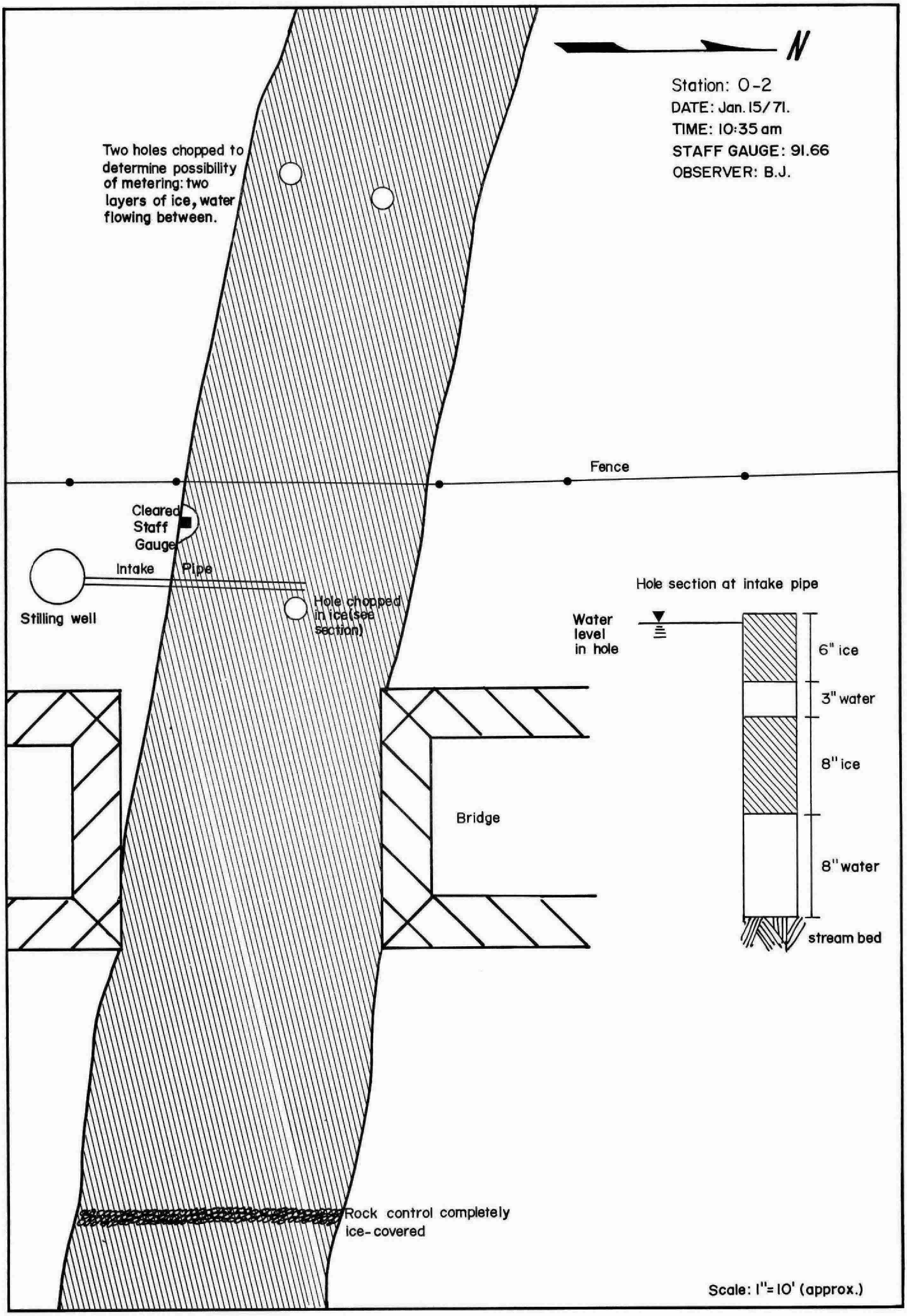

Station: O-4
DATE: Feb. 23/70.
TIME: 11:00
STAFF GAUGE: 90.85
OBSERVER: B.J.
Bridge
Fence
N
Note:
- Water level the same on both sides of control
- Backwater caused by ice and anchor ice jamming downstream
- Backwater partially relieved by clearing jammed ice
Surface ice & slush
Water flowing over 12" ice
Surface ice & slush
Stilling Well
Staff Gauge
Weir
Jammed surface & anchor ice, flow over & beneath ice
Approx. scale: 1" = 12.5' horizontal
1" = 25.0 vertical

Ice sheet 11

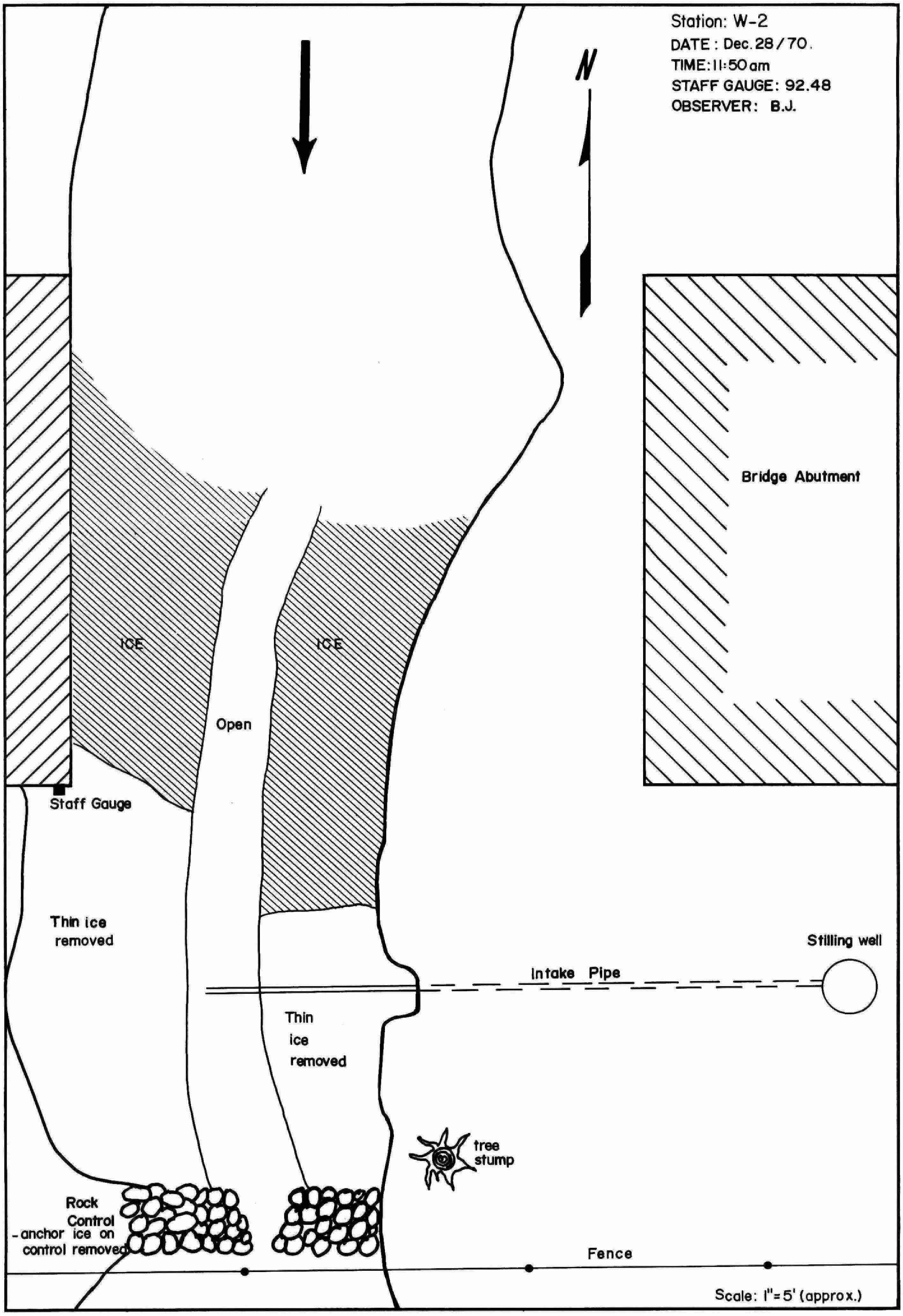

N
Station: B-3
DATE: Jan.4/71.
TIME: 12:15 pm.
OBSERVER: B.J.
Open
ICE
Fence
Section A-A cleared at notch
ICE
1' open
approx. 3" clearance between
ice & streambed
Note:
- No correction due to backwater
but probably correction due to
pressure build-up in weir pond
due to reduced area
A
Cleared
Open
A
Staff
Gauge
Control
Stilling
Well
Open
Bridge
Not to scale

Ice sheet 12


Station: B-3
DATE: Jan. 13/71.
TIME: 12:45pm.
OBSERVER: B.J.
N
ICE
Fence
Section A-A: 2' upstream of control
Ice
open
≈8"
≈8" open
ice frozen on bottom
2"-3" clearance
Ice cleared
Note: - Ice cleared from weir pond was causing a difference of 0.04' between tape & S.G.. Reading after clearance 0.02' difference. Check chart.
- Backwater relieved by clearing ice from downstream end of culvert.
A
A
Staff Gauge
Control
Stilling Well
Bridge
Not to scale


N
Station: O-2
DATE: Jan. 15/71.
TIME: 10:35 am
STAFF GAUGE: 91.66
OBSERVER: B.J.
Two holes chopped to determine possibility of metering: two layers of ice, water flowing between.
Fence
Cleared Staff Gauge
Intake Pipe
Stilling well
Hole chopped in ice (see section)
Hole section at intake pipe
Water level in hole
6" ice
3" water
8" ice
8" water
stream bed
Bridge
Rock control completely ice-covered
Scale: 1"= 10' (approx.)

Ice sheet 14



Station: W-2
DATE : Dec. 28 / 70.
TIME: 11:50 am
STAFF GAUGE: 92.48
OBSERVER: B.J.
N
Bridge Abutment
ICE
ICE
Open
Staff Gauge
Thin ice
removed
Stilling well
Intake Pipe
Thin
ice
removed
tree
stump
Rock
Control
- anchor ice on
control removed
Fence
Scale: 1" = 5' (approx.)

Ice sheet 15